

VISIT...

LANZAROTE
Caliente.COM

Upper Extremity Neuroprosthetics

Douglas T. Hutchinson, M.D.

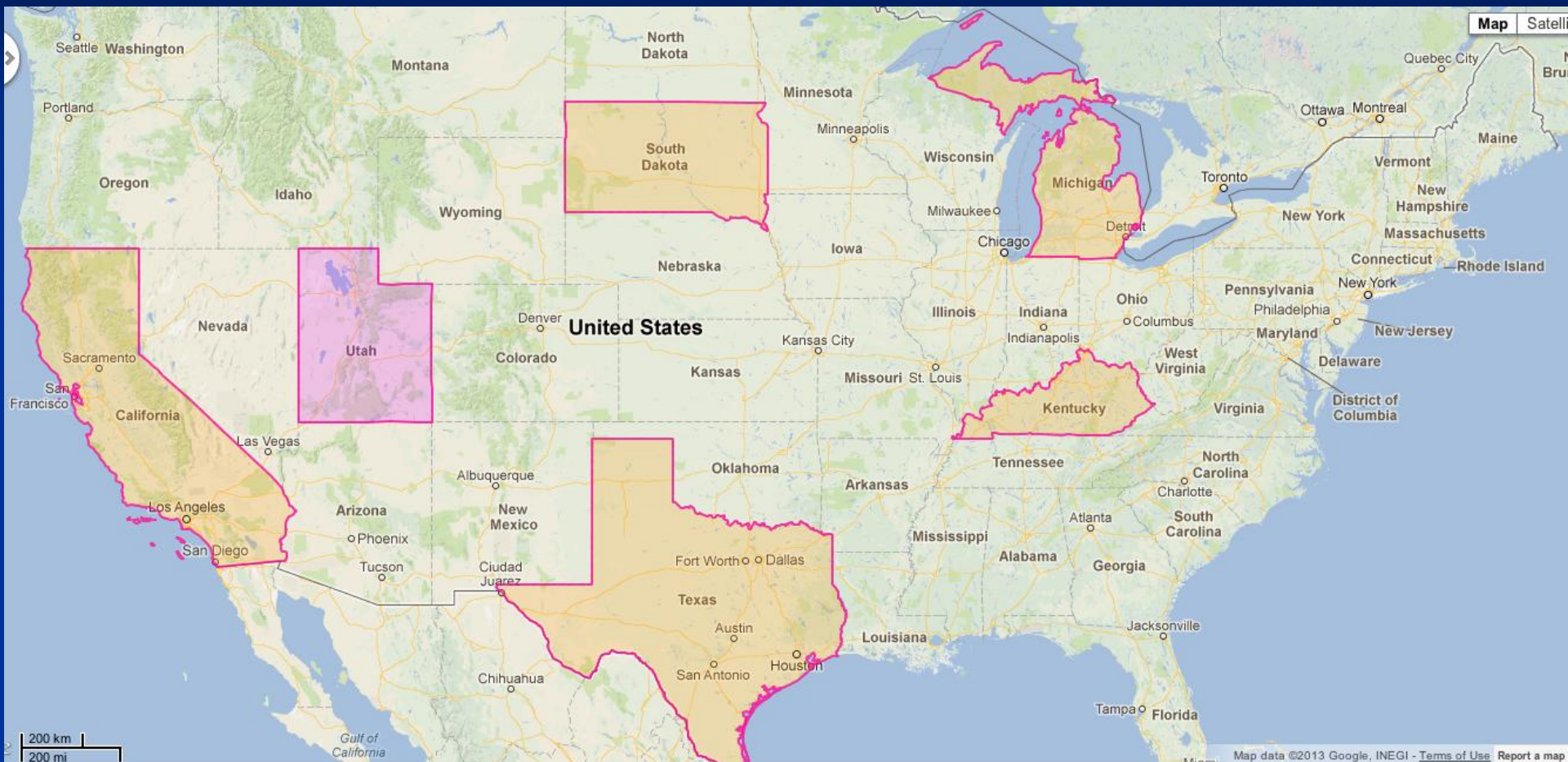
**Associate Professor
Orthopaedics**

**Associate Professor
Bioengineering**



Geography Lesson!!











TEAM-U of Utah

Bradley Greger, PhD

Richard Normann, PhD

Heather Wark , BS

Greg Clark, PhD



Neuroprosthetics

Rx:

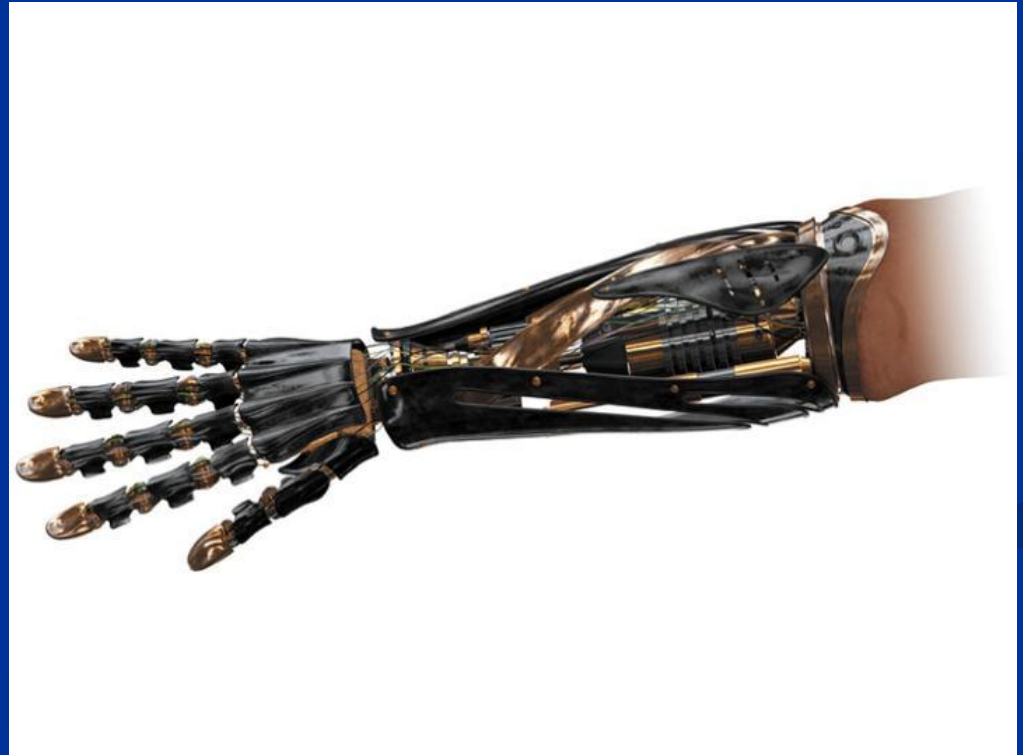
SCI

UEA

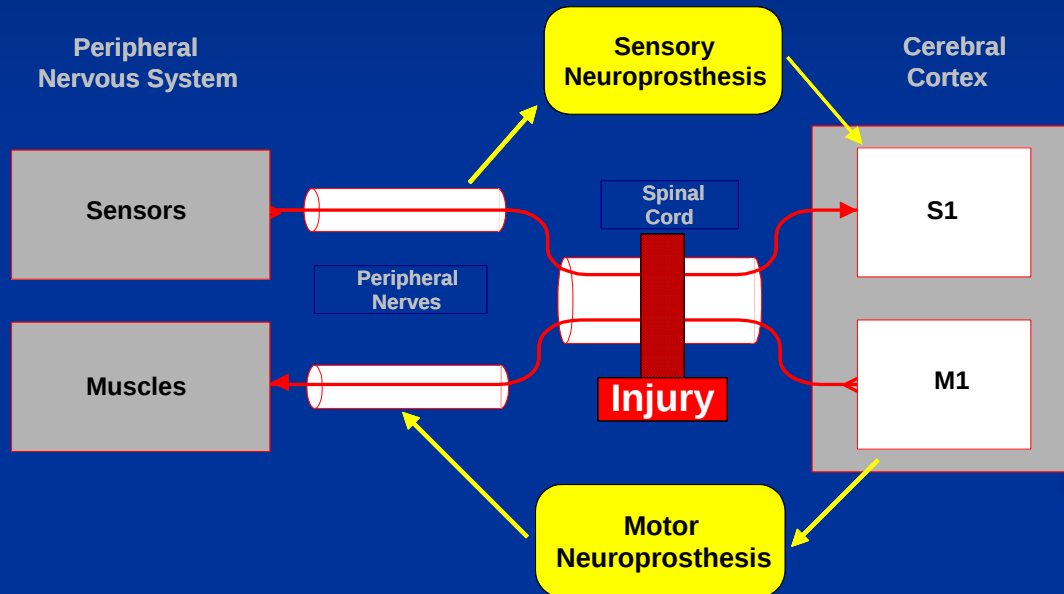
CP

BPP

NPP

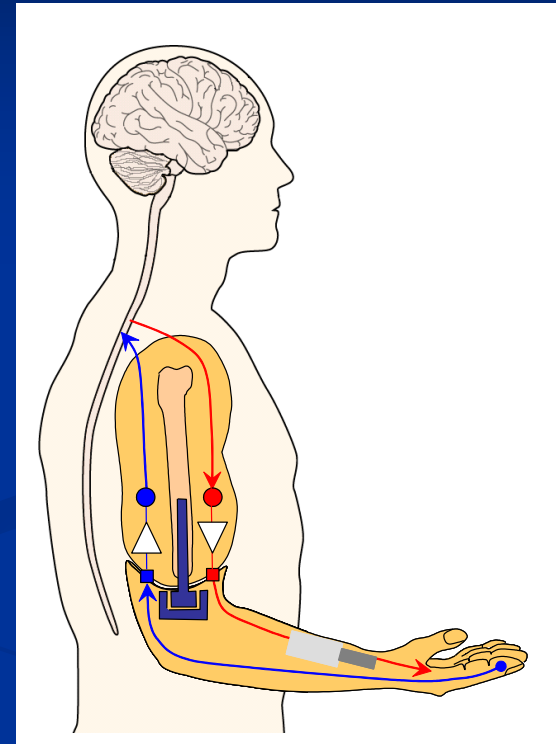


Spinal Cord Injury (SCI)



**Limb intact,
signals missing**

Prosthetic Limbs



(Kandel et al., 2000)

**Signals intact,
limb missing**

SCI

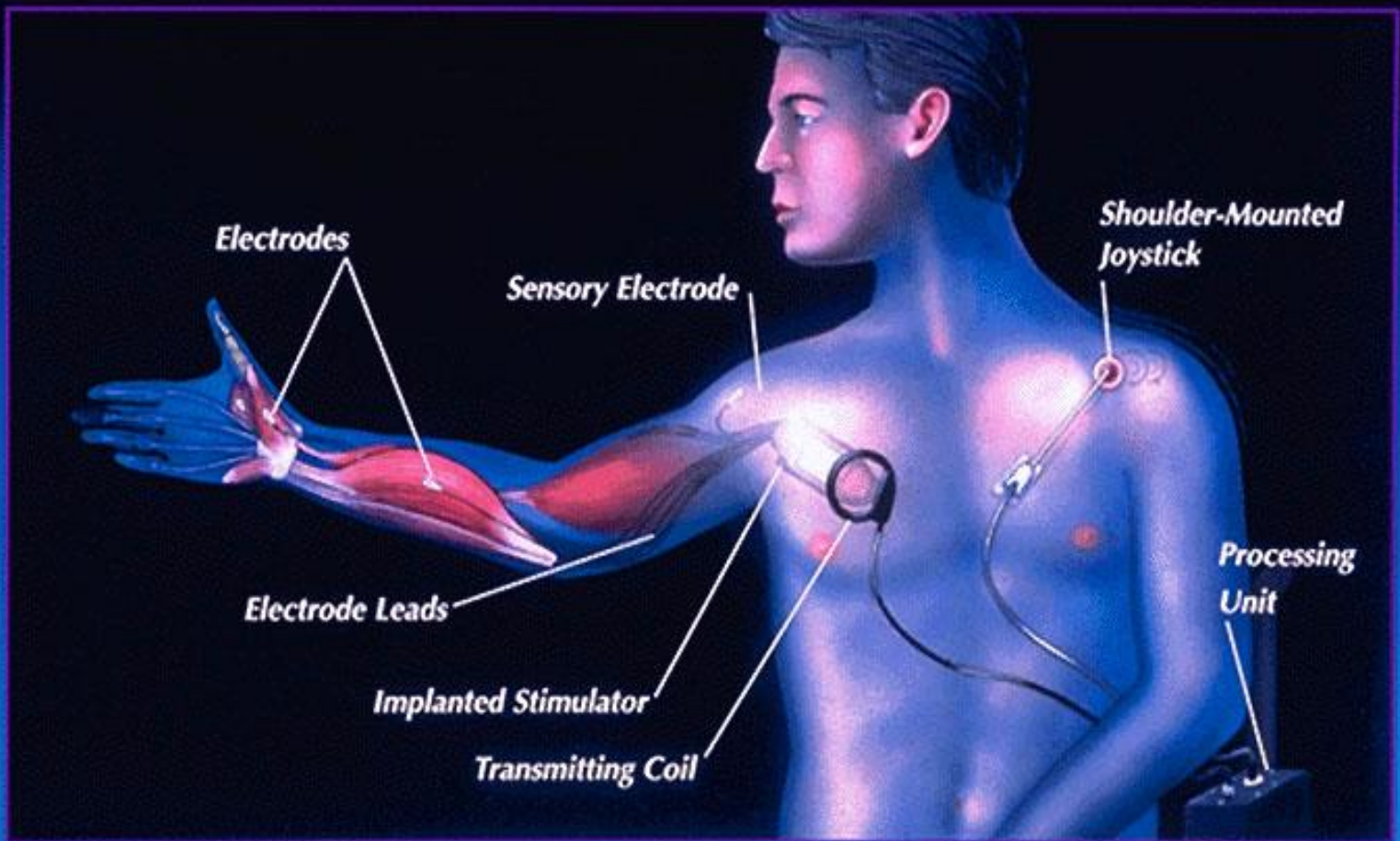
1) **Functional Electrical Stimulation (FES) Upper Extremity (Freehand)**

Michael Keith, M.D. – Case Western

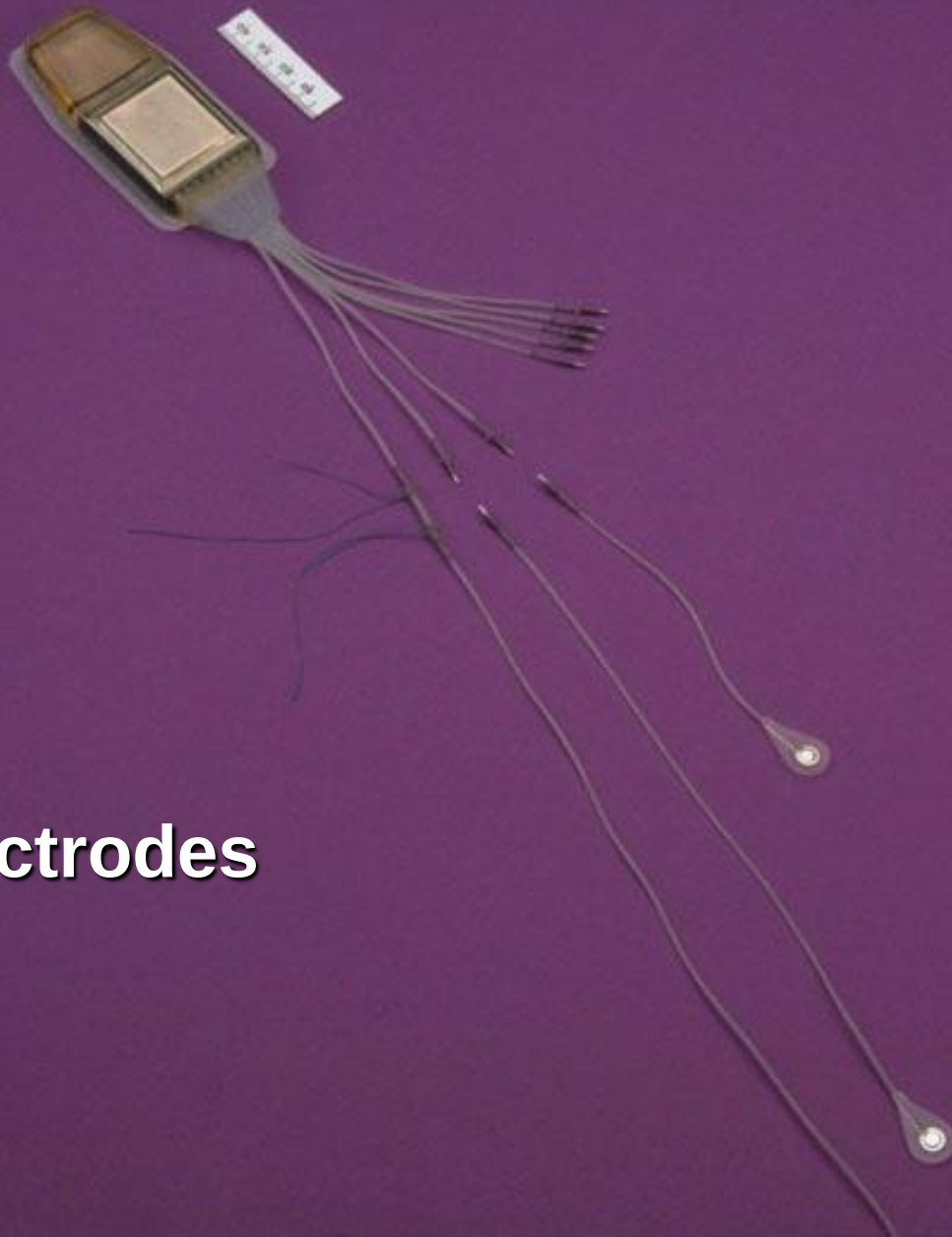
2) **Standing/Gait**

U of Miami, Case Western, University of Utah

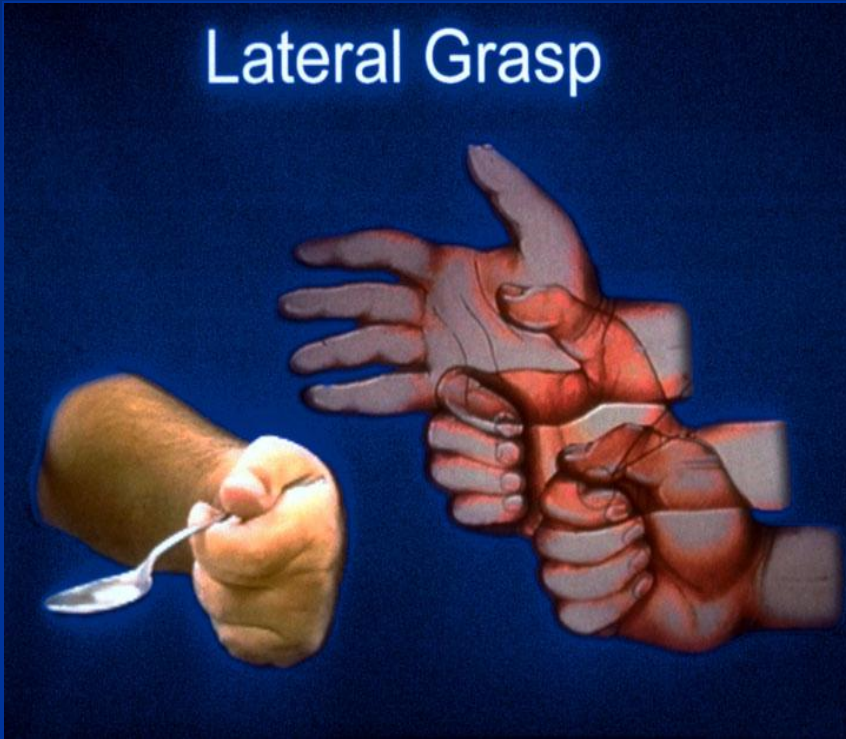
The Freehand System by NeuroControl Corporation



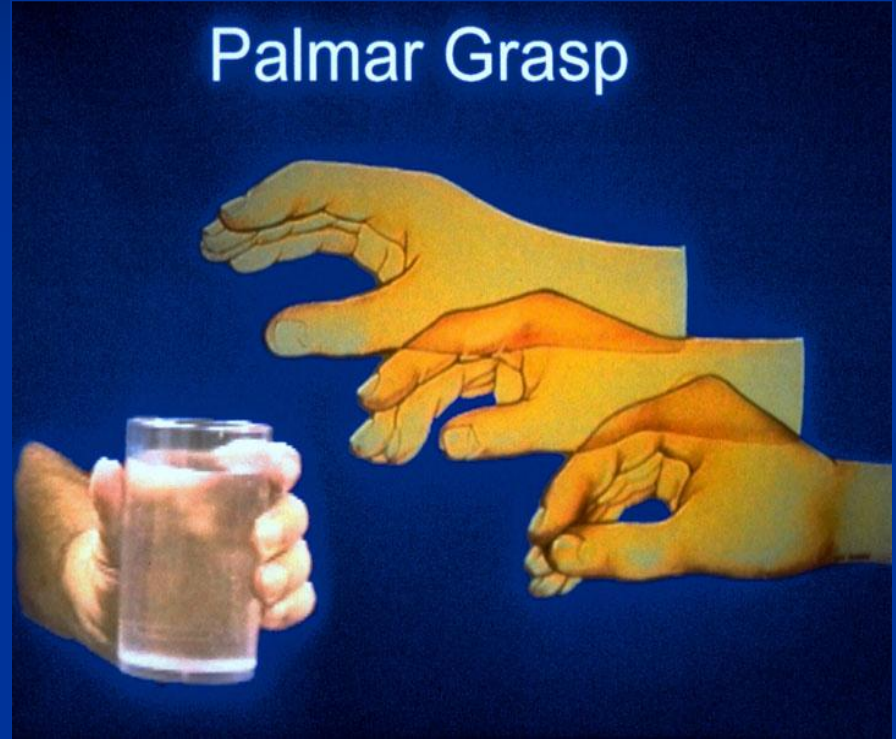
8 Electrodes



Lateral Grasp



Palmar Grasp



Freehand - Challenges

Wires = # Muscles

Invasive

Sensory Feedback

Muscle Fatigue

Re-programming

Money

Claire Lomas Finishes London Marathon in 16 Days!



Upper Extremity Amputation

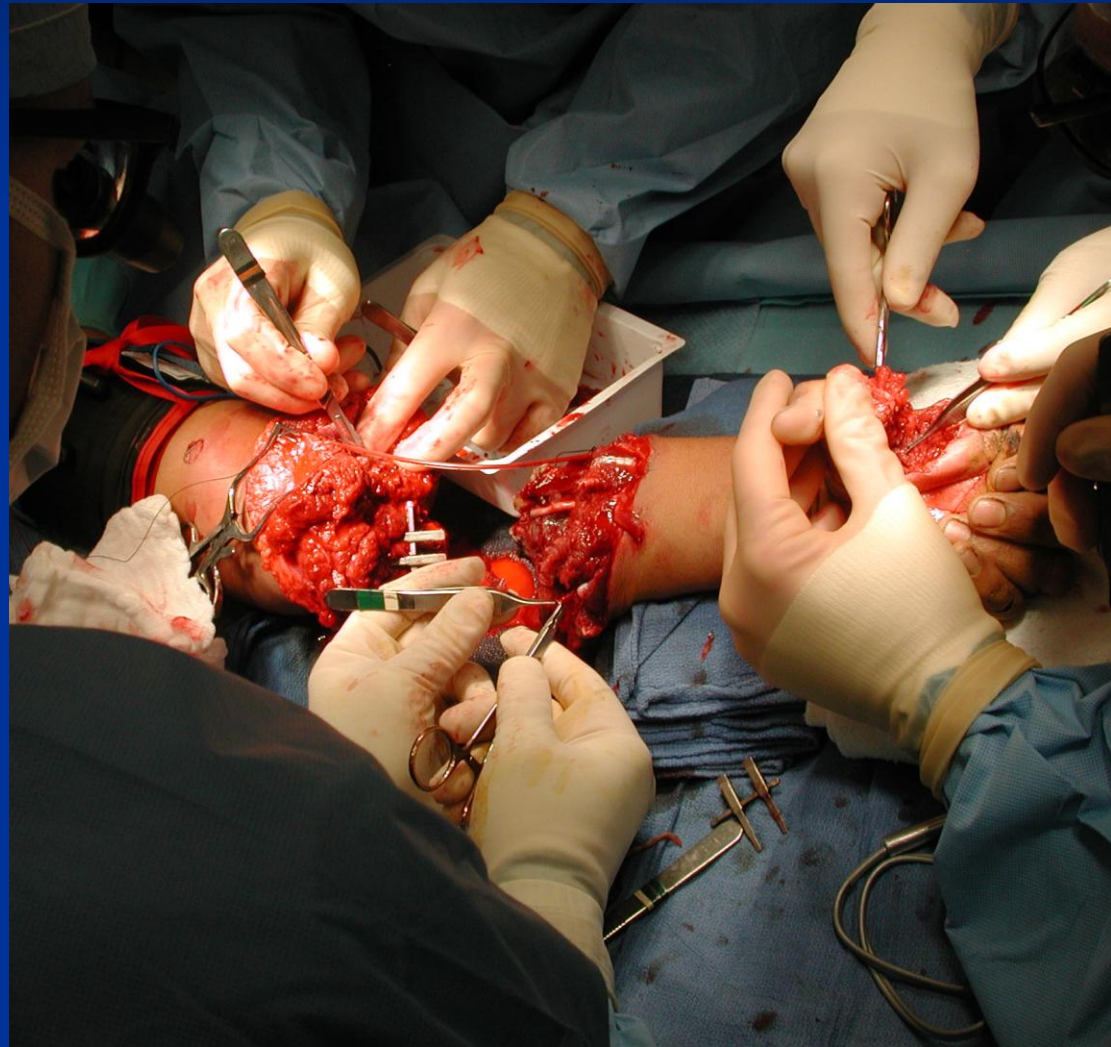


Replantation Ischemic Time

- Literature ranges 4-33 hrs.
average =10
- Muscle death – 6 hrs.
- Capillary permeability – 2 hrs.

Macroreplantation

- Team
- Survival 30-80%
- Complications high including death
- Functional outcome variable





Not Replantable

Iraq/Afghanistan War

- Increase use of body armor
- Increase use of man made explosives



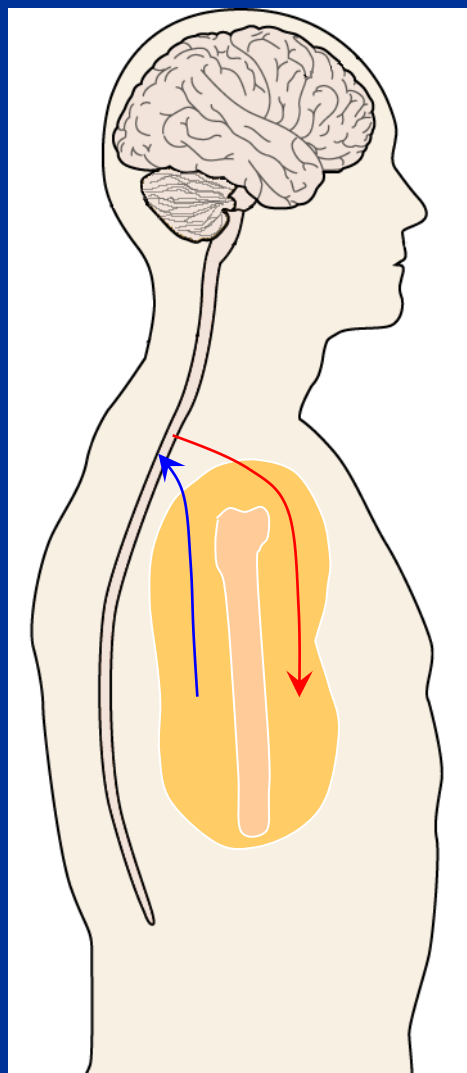
Result = many healthy amputees

Amputation



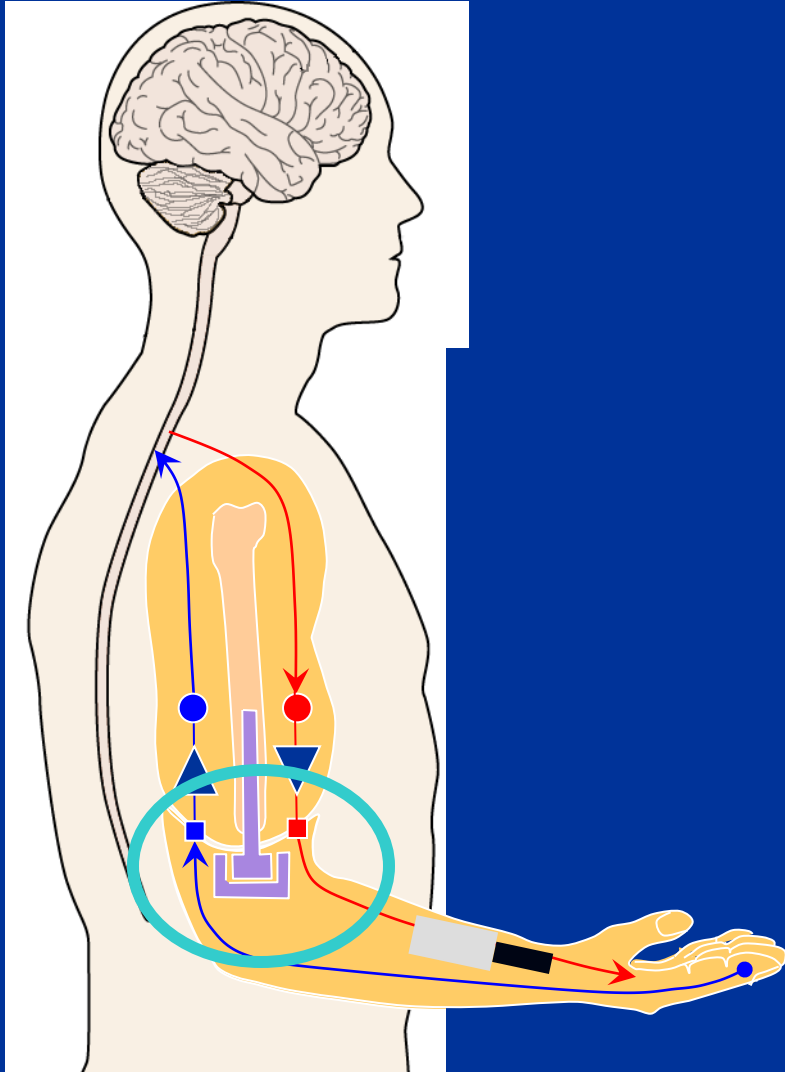
Hand Transplantation

- Louisville
- Pittsburgh
- Johns Hopkins
- Tuscon
- L.A.?
- NYC?
- Boston?



Connection

- Osseointegrated implant
- Break-away binding
- Infection control



Bloebaum/Bachus U of Utah
Branemark Sweden



Roy D. Bloebaum, Ph.D.

Kent N. Bachus, Ph.D.

“Development of Osseointegrated Implants for Soldiers Following Orthopaedic Extremity Trauma”

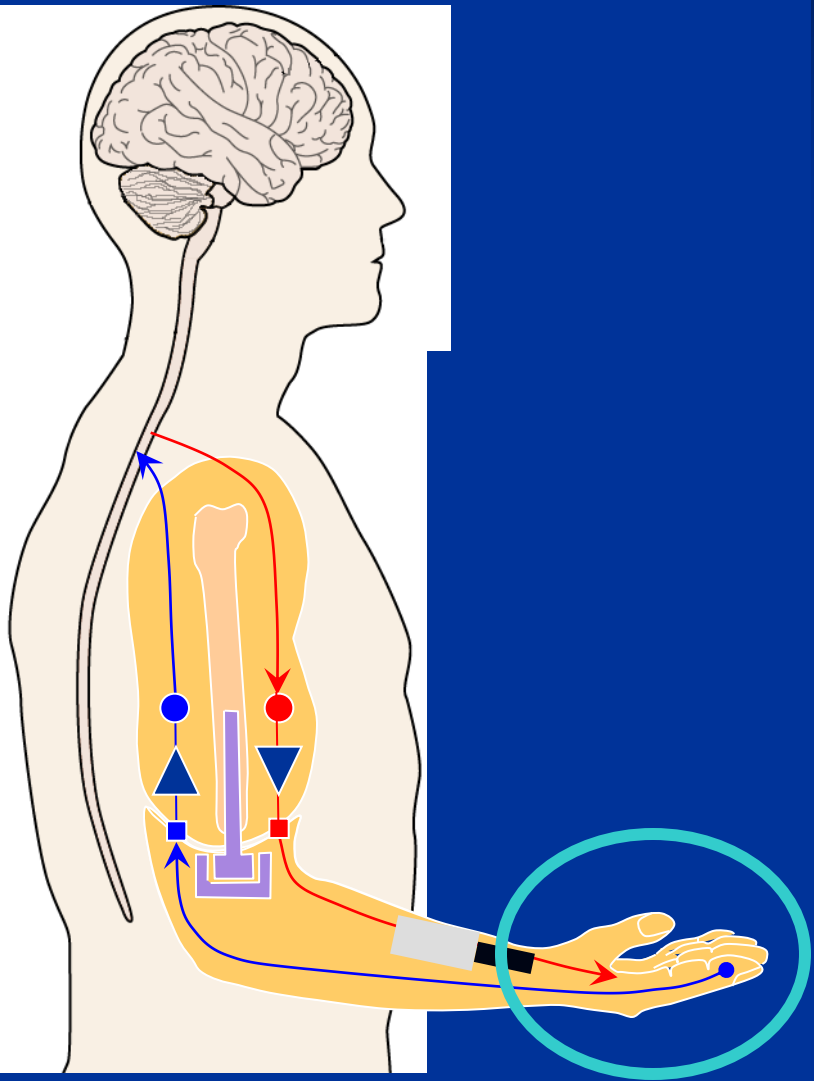
The Department of Defense

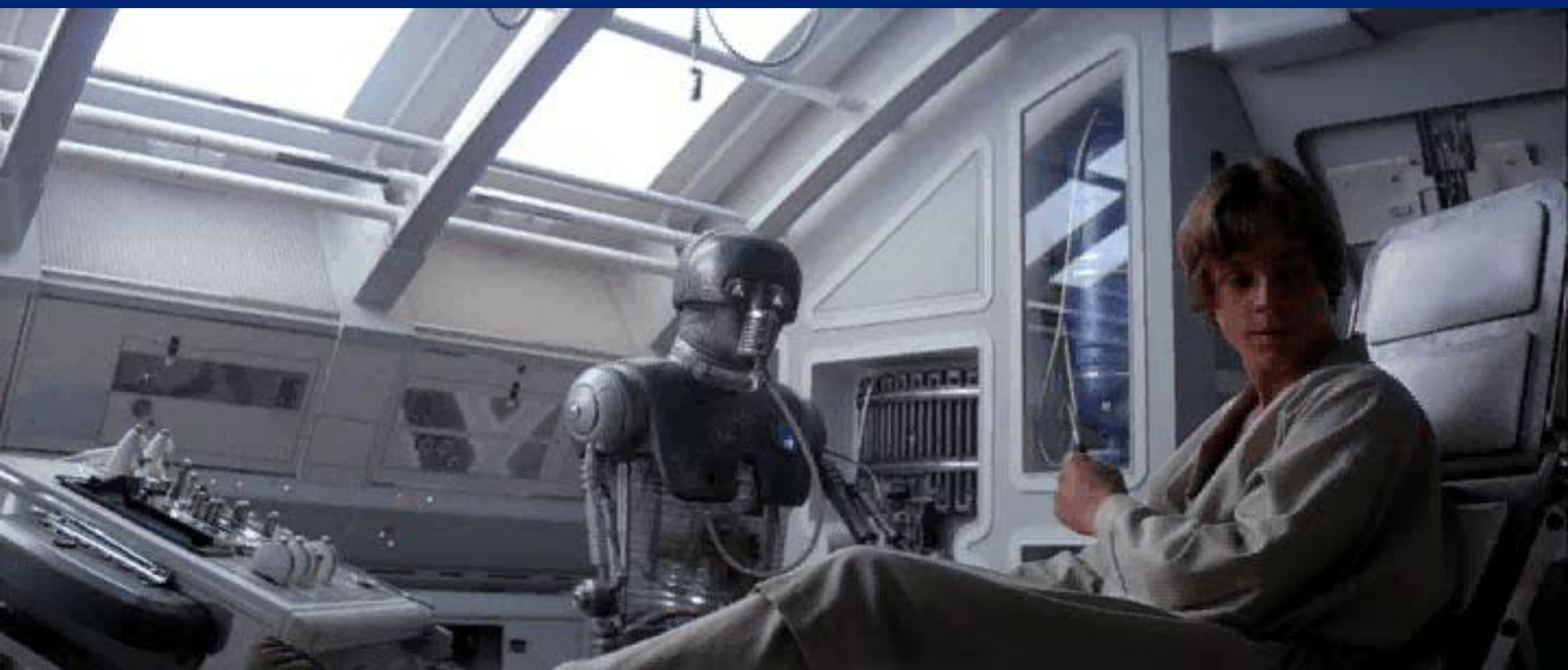
U.S. Army Medical Research and Materiel Command (USAMRMC)

Congressional Directed Medical Research Programs (CDMRP)

Prosthetic Limb

- Lighter materials
- Waterproof
- More degrees of freedom
- More motors
- Actuators, sensors



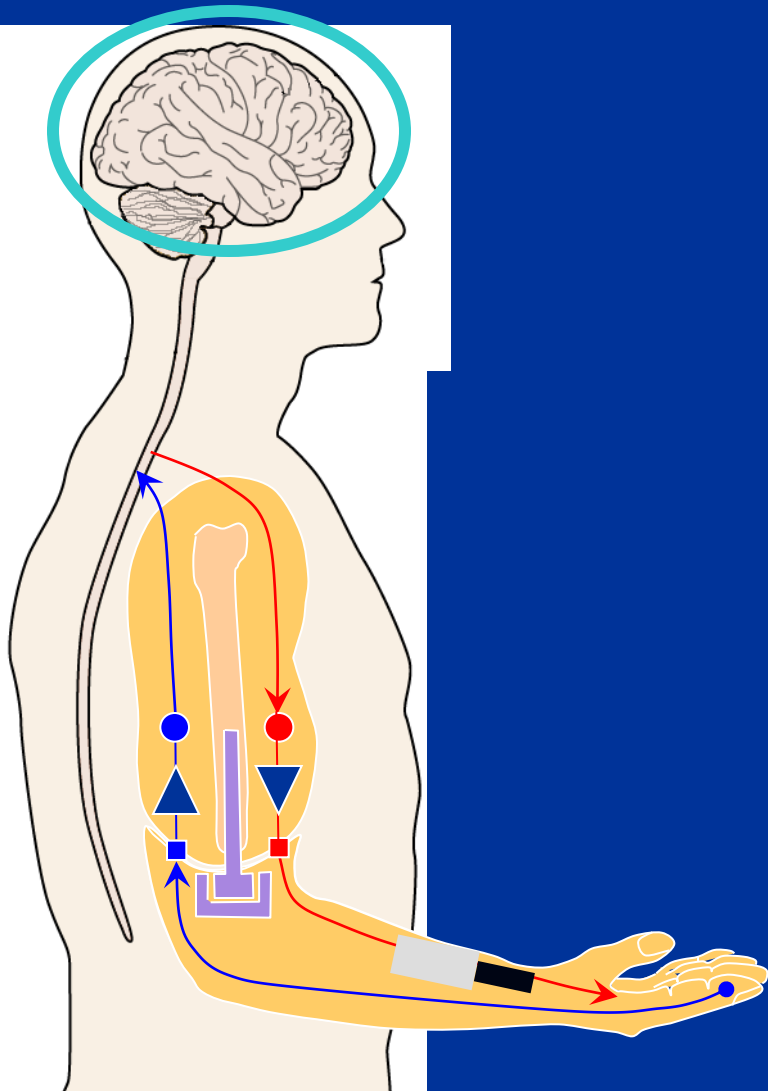


**Vanderbilt University
Multi Grasp Prosthetic Hand**

C.N.S.

Direct connection

Peripheral nerve connection

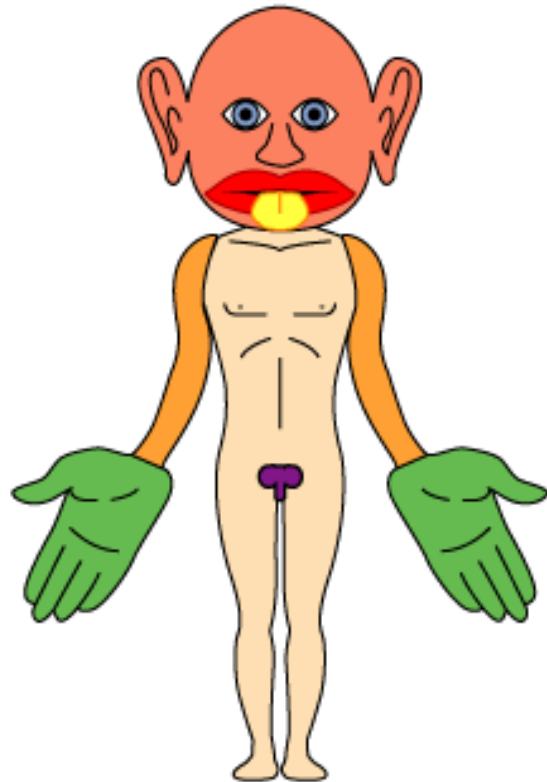


Direct CNS Control



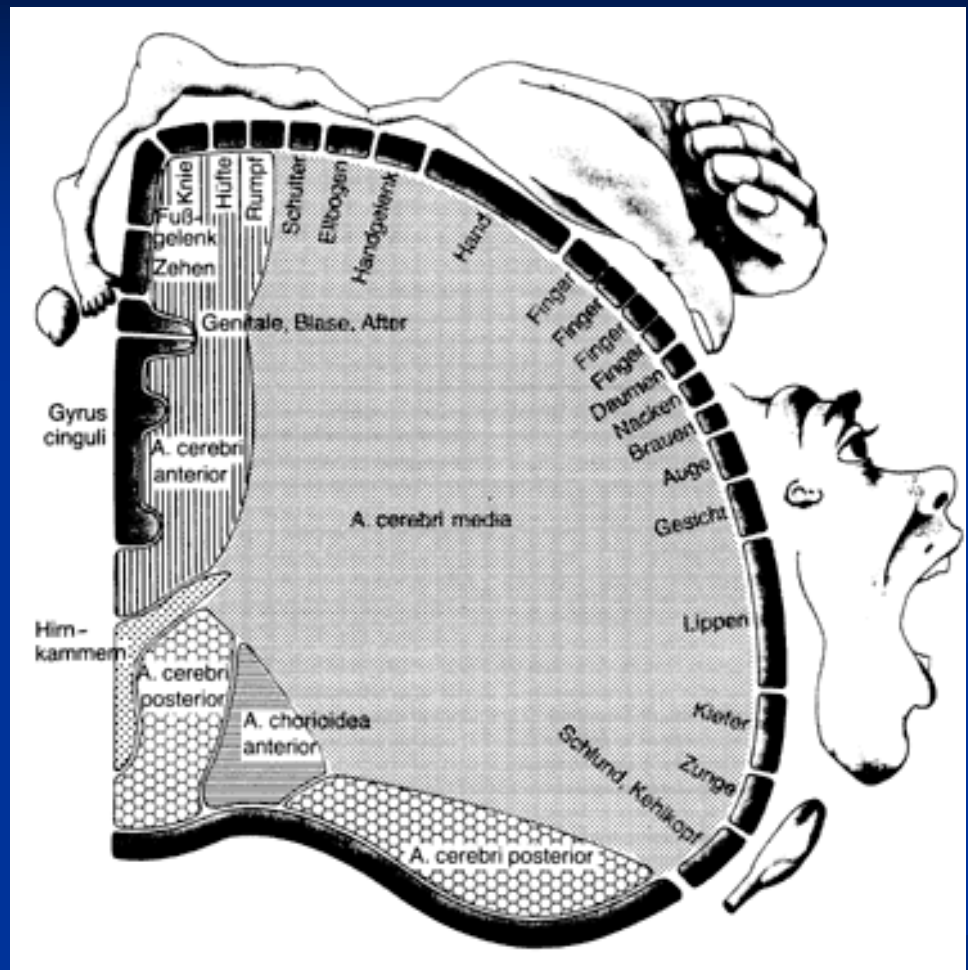
If I were Rob Strauch, I would have a 60 minutes clip here!



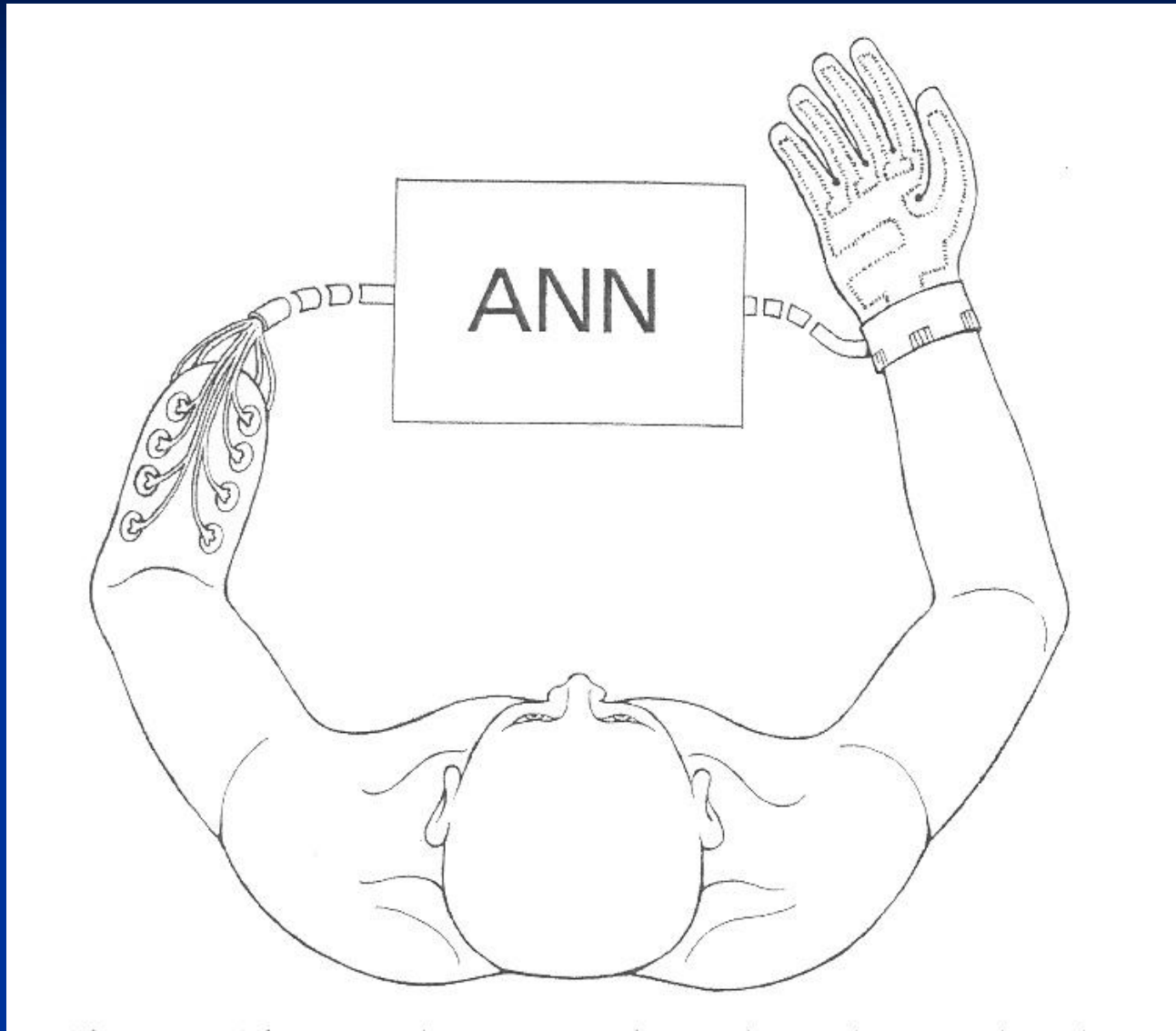


**Simple Representation
of the Sensory Cortex**

©2001 HowStuffWorks



Artificial Neural Networks

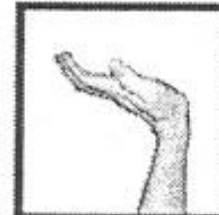


M1



Little and ring finger
flexed together

M6



Extension of the
wrist

M2



Middle finger flexed

M7



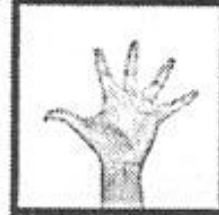
Flexion of the wrist

M3



Index finger flexed

M8



Abduction of the
fingers

M4



Thumb in
opposition towards
the base of the little
finger

M9



Adduction of the
thumb

M5



All fingers flexed
together

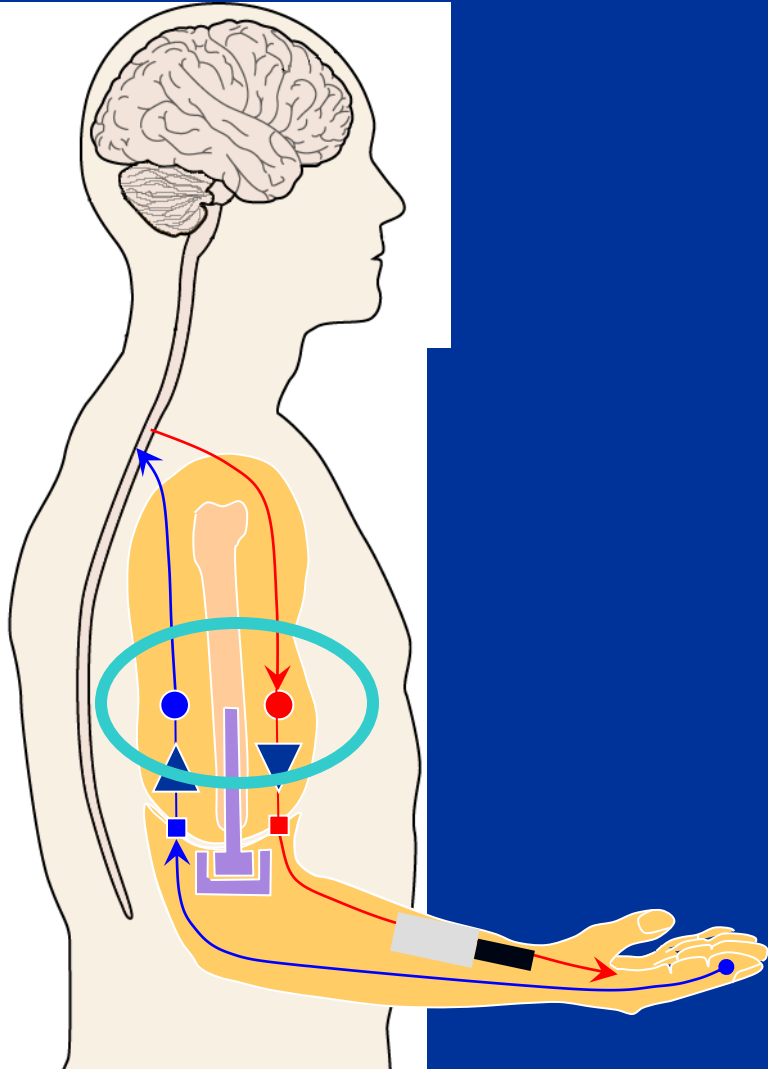
M10



Flexion of the IP
joint of the thumb

Conclusion

- **Brain plasticity – can be retrained**
- **Using intact peripheral nerve reasonable**



Controller

- Muscle
- Neural

Myoelectrics

- Use remaining muscle to control one function of prosthesis
 - Availability
 - Gross motions
 - Retraining (not natural)





Enhanced Myoelectric Control

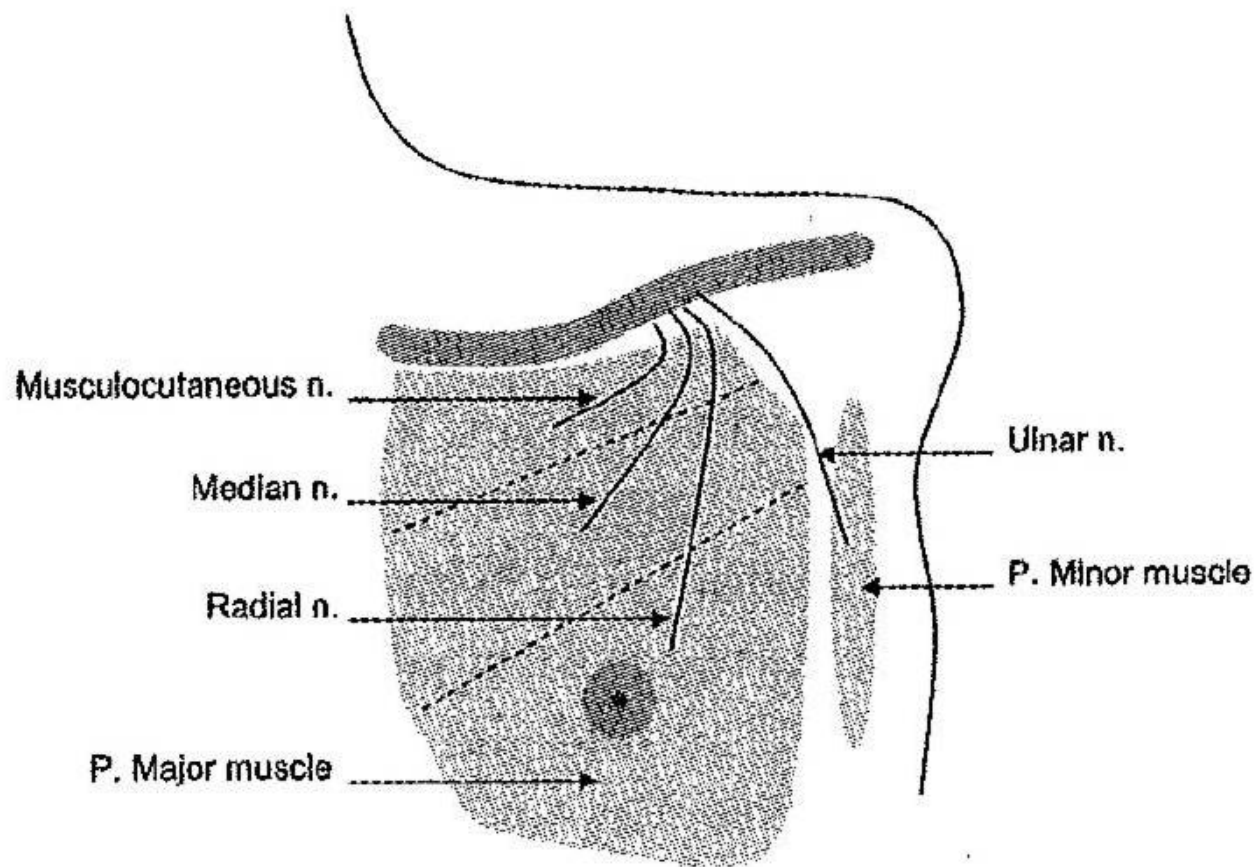


Fig. 1. Diagram of nerve-muscle graft procedure.



Courtesy of DEKA Research & Development and
The Rehabilitation Institute of Chicago

IMES

- Intramuscular Electrical Stimulation
- Wireless
- Small
- Can place in specific residual muscles



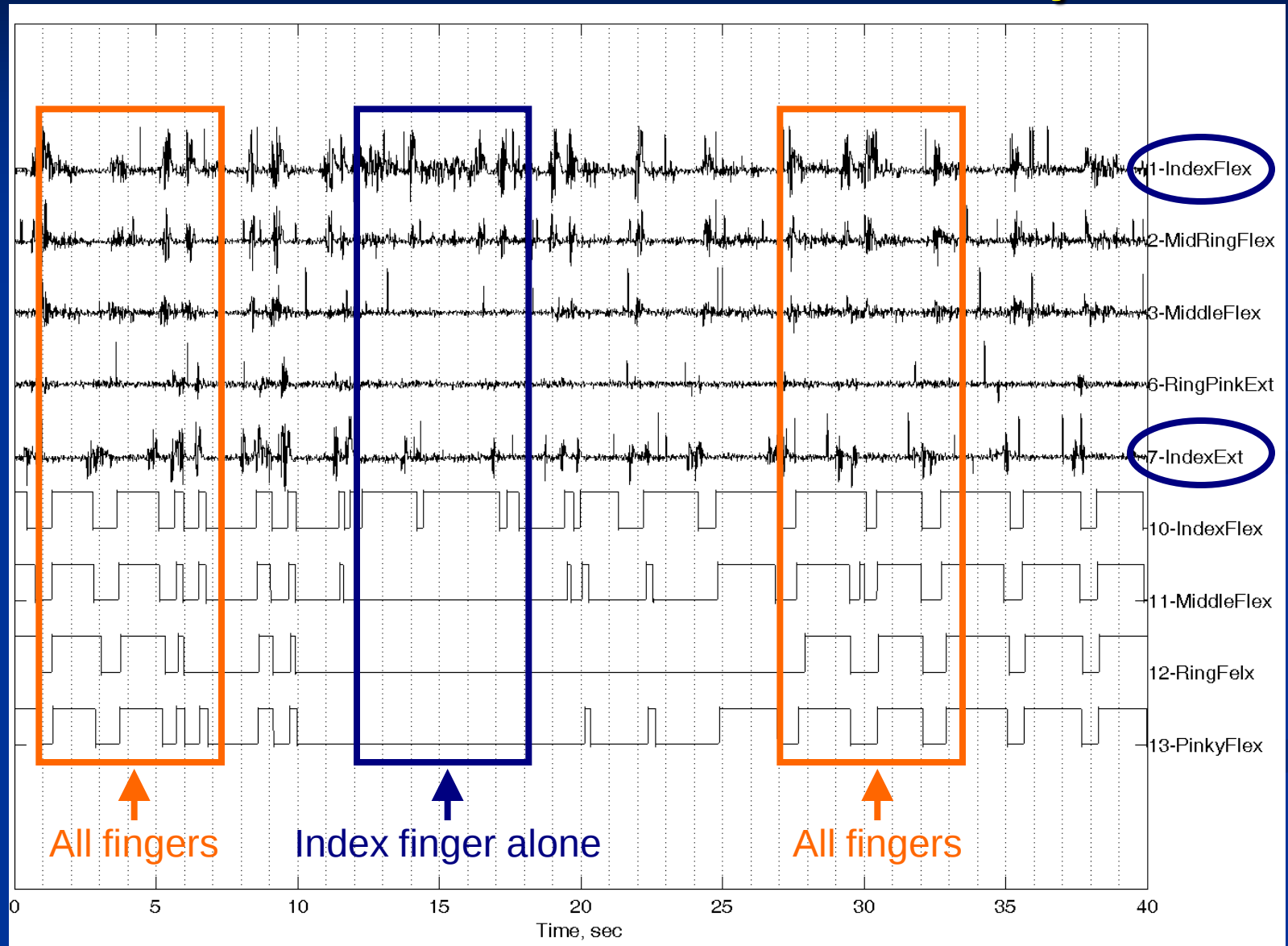
IMES



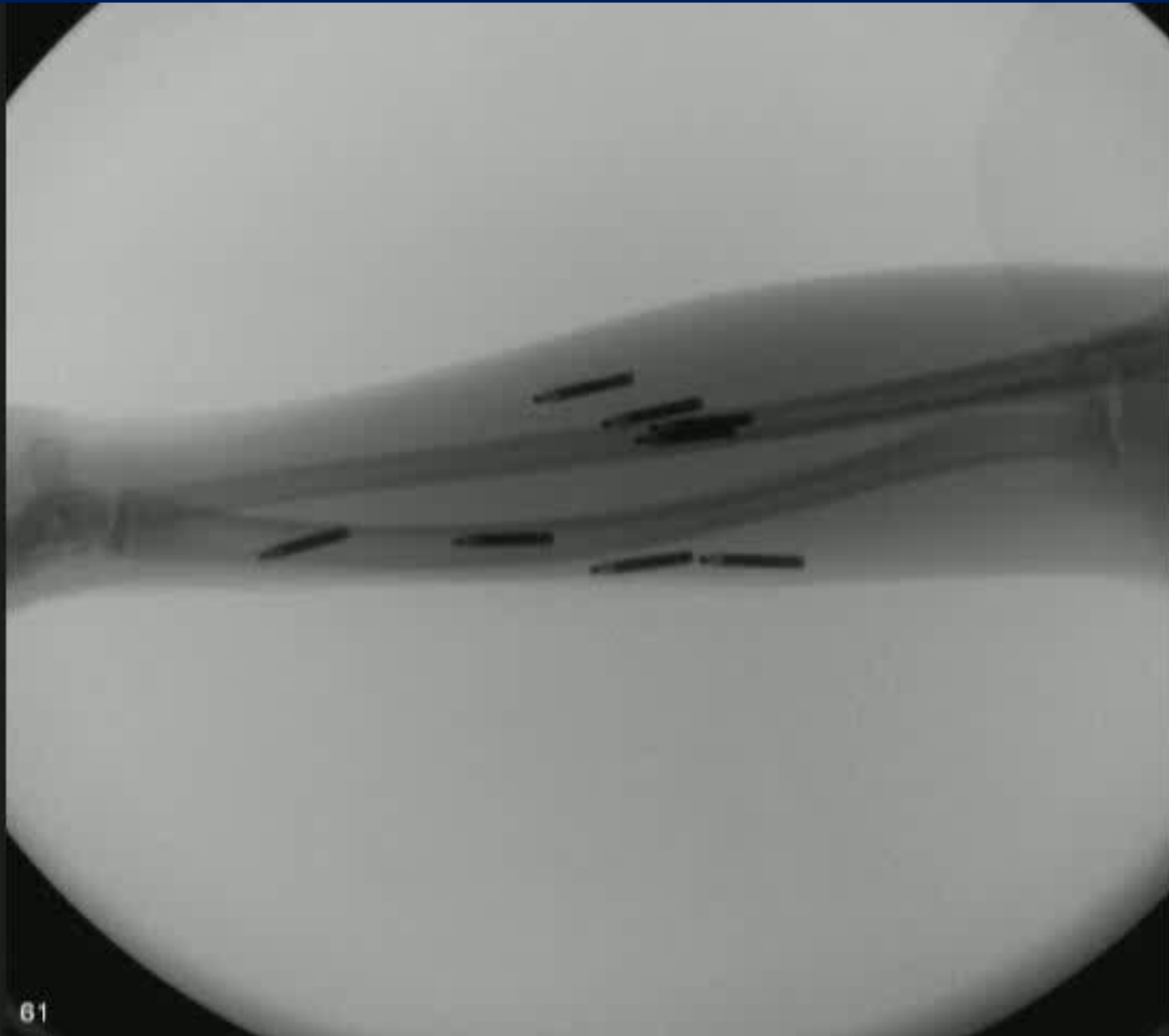
IMES



Manipulandum Switch Closures



IMES: REAL TIME X-RAY VIDEO



Direct Nerve Interface

- **Would allow low current input/high force output**
- **Patient could simply think about task**
- **Multiple simultaneous motions**
- **Sensory feedback readily available**

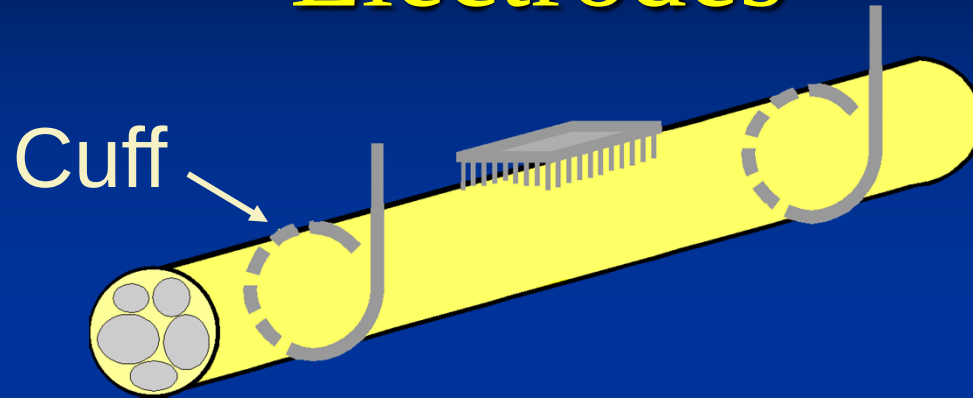
Direct Neural Interface

Problems

- 1) Will the nerve stump function?**
- 2) Infection control**
- 3) Connection to nerves**

Nerve Stump Connection

Peripheral Nerve Stimulation: Cuff Electrodes



Advantages (relative to muscle stimulation)

- Lower stimulation thresholds (1-20 mA) than muscle electrodes

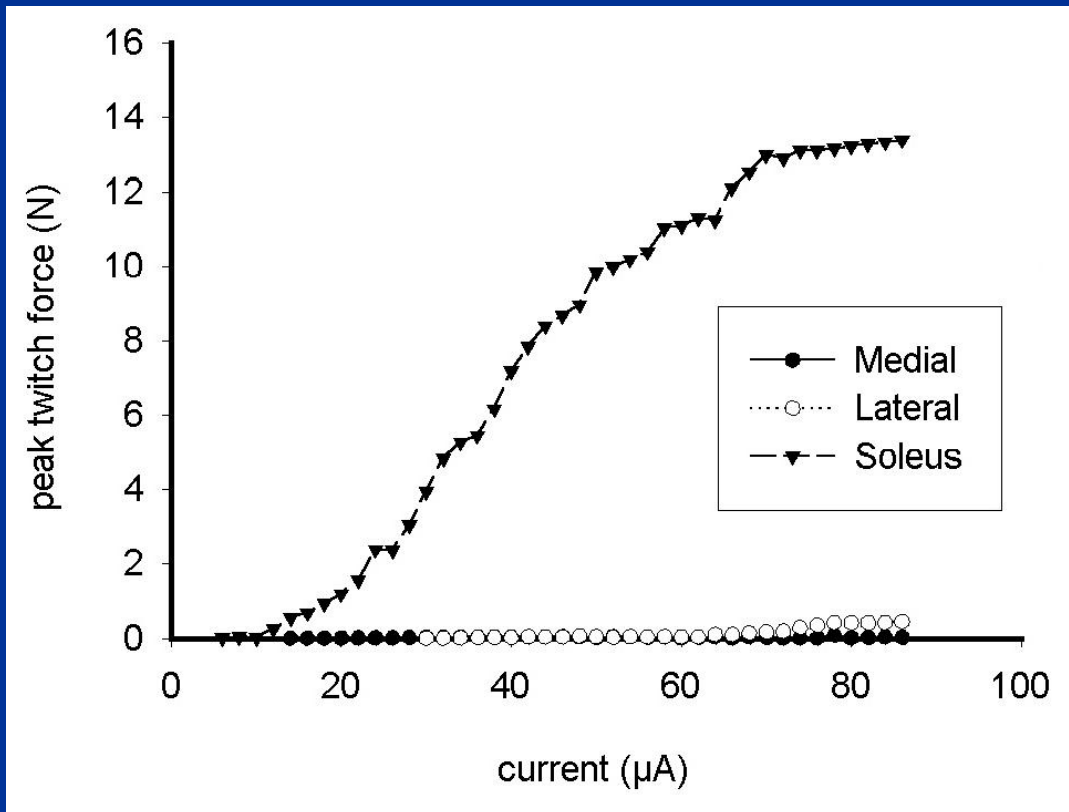
- Accesses multiple muscles; relatively easy to implant

Disadvantages

- Poor muscle selectivity: activate many (even opposing) muscles

- Poor force gradation

Enhanced Force Control and Between-Muscle Selectivity



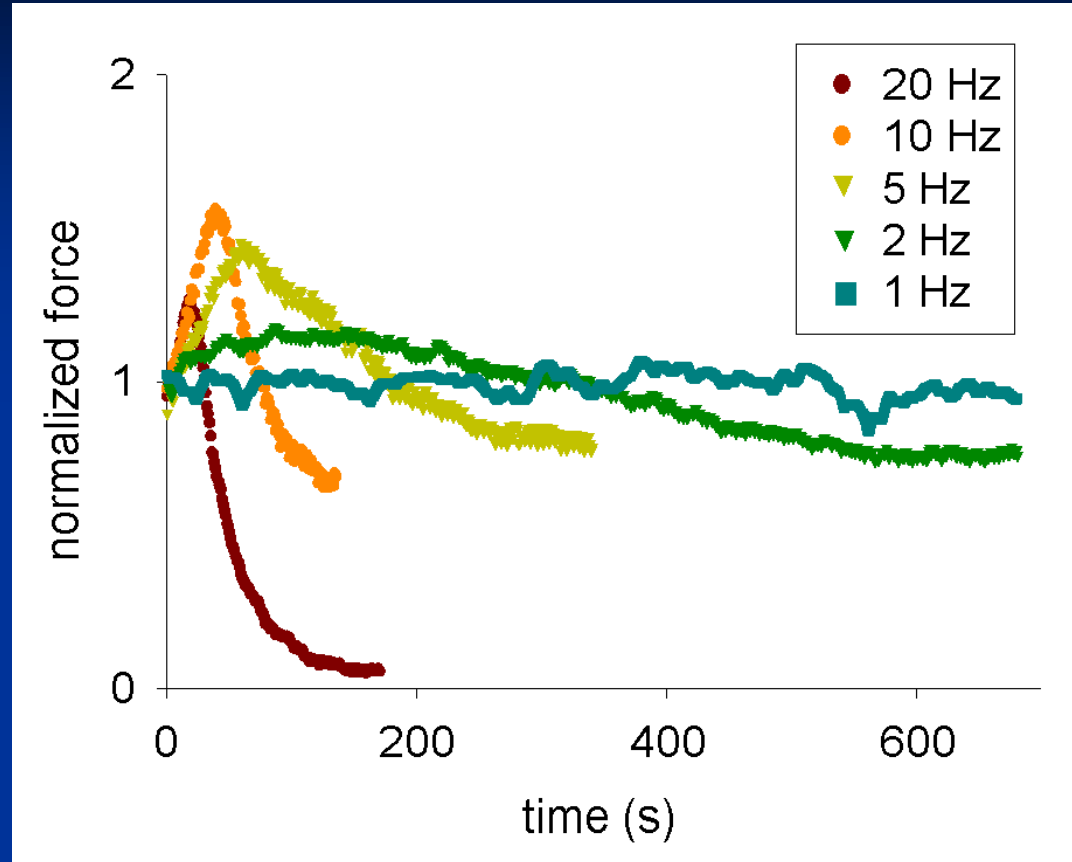
■ Force

- Highly controllable over full dynamic range

■ Selectivity

- Virtually no activation of other muscles, even at maximum forces

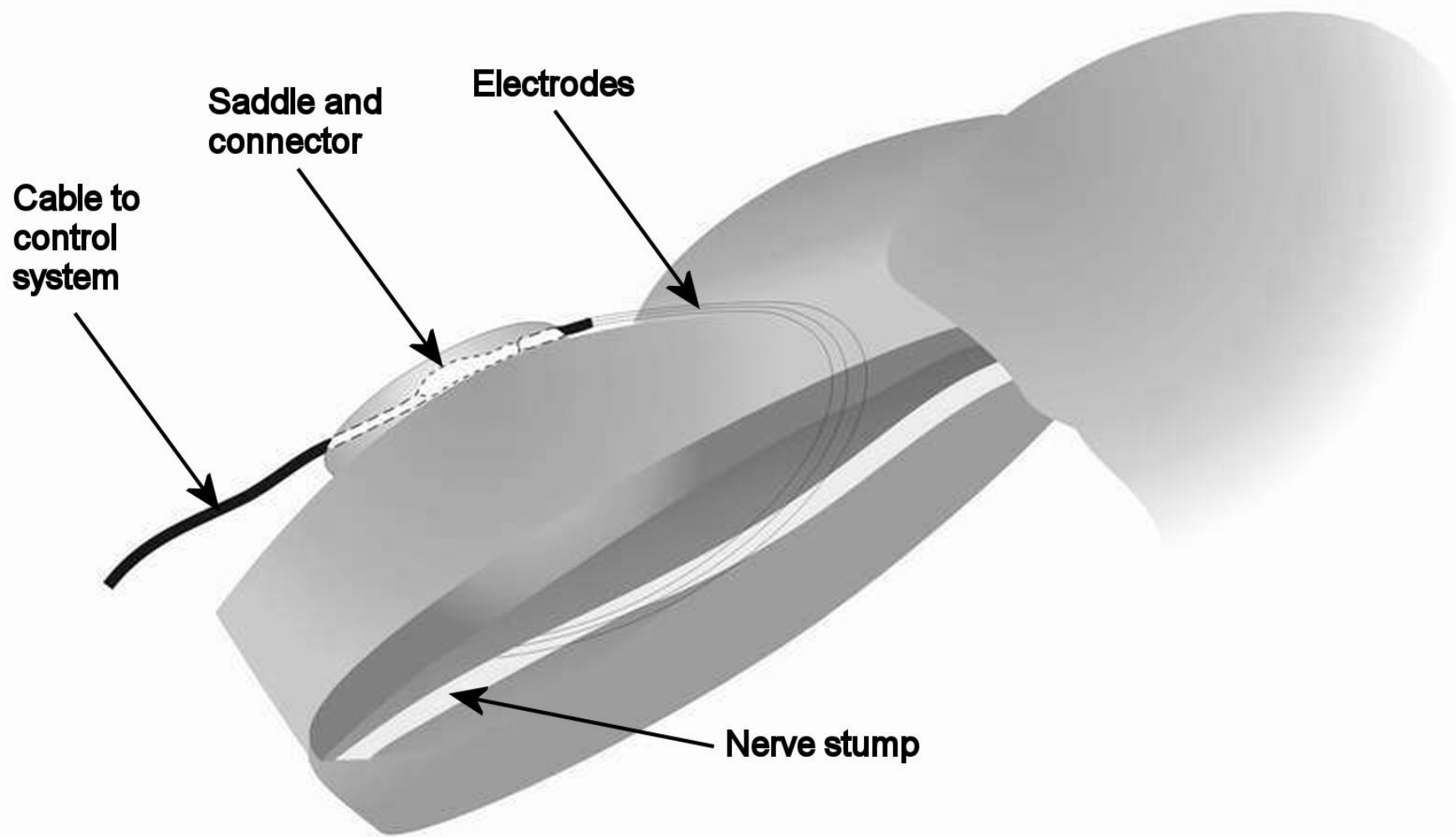
Extremely low-frequency stimulation



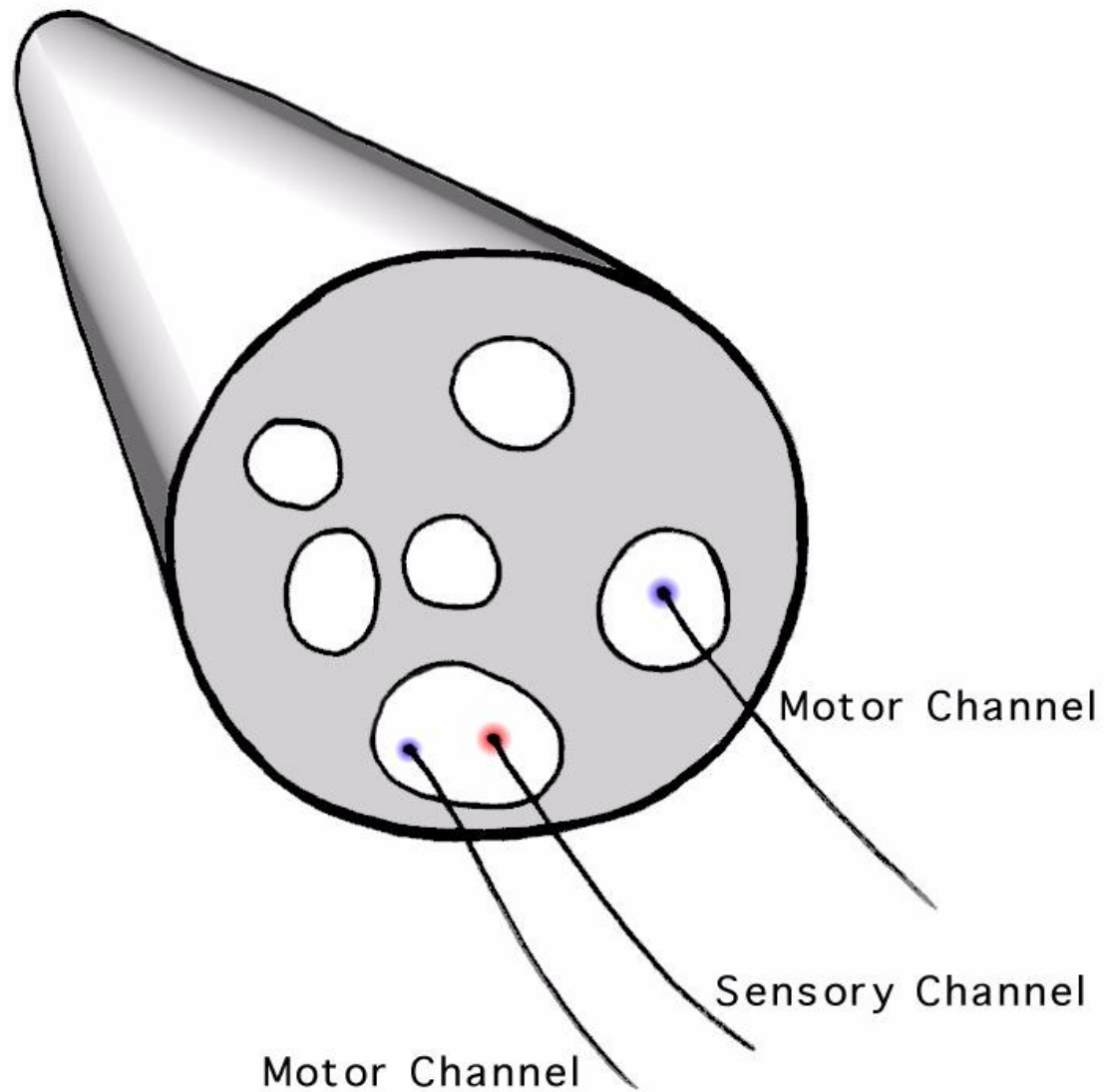
- Reduces fatigue
- Reduces potentiation
- **RESULT: Maintains target force**

LIFES

- Longitudinal Intrafascicular Electrical Stimulation
- Horch, Meek, Dhillon, Hutchinson
U of Utah Bioengineering



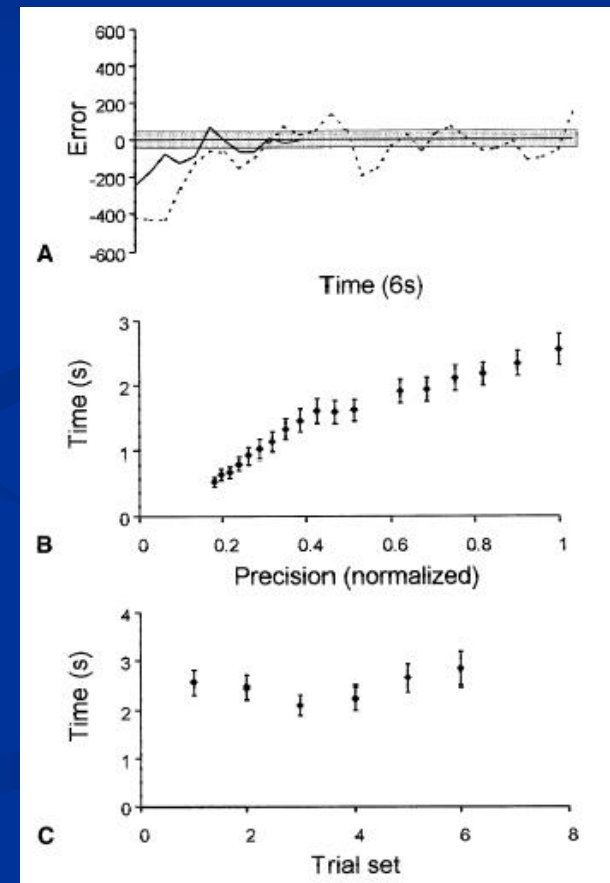
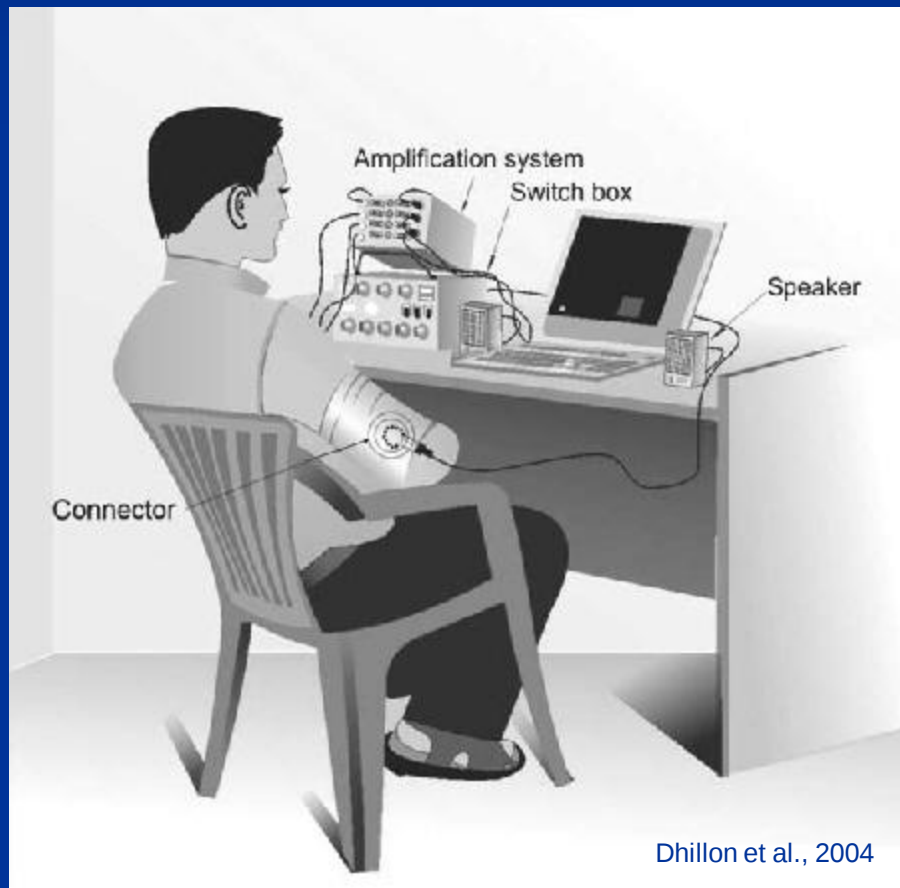
Implanted HLIFEs in Amputee Nerve Stump



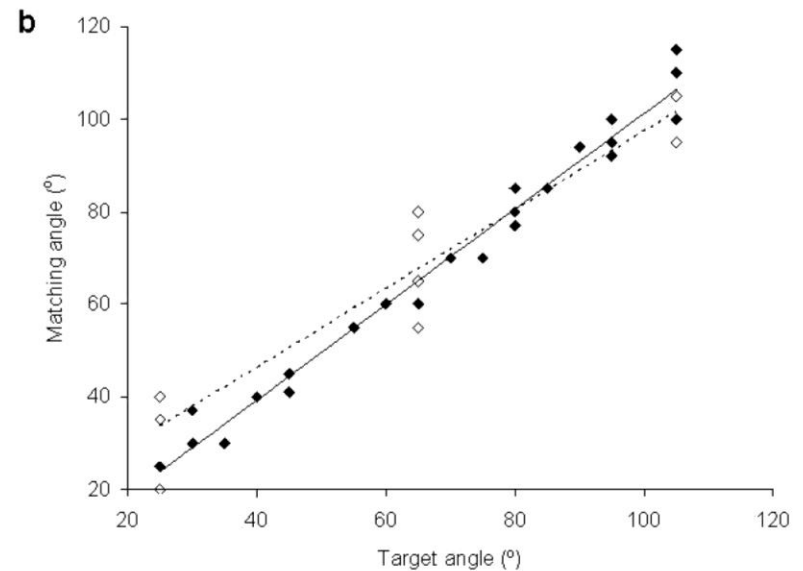
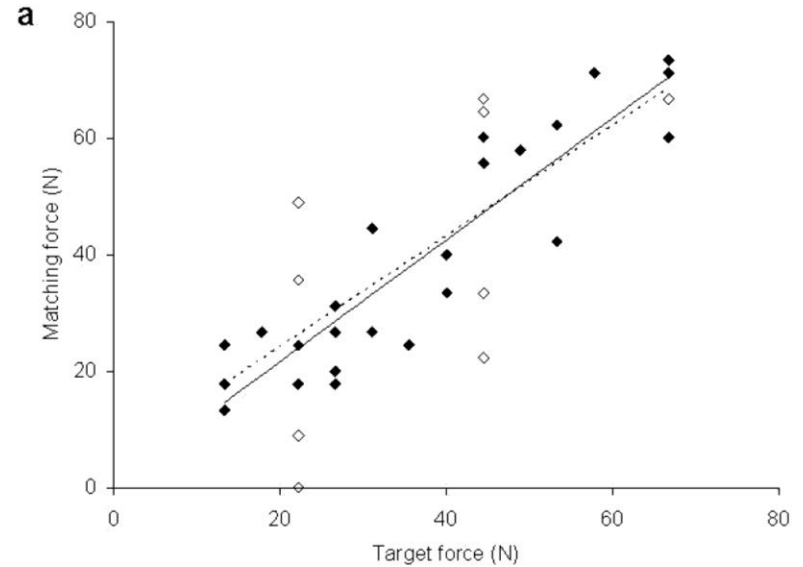
Do Residual Nerves Remain Viable After Amputation?

Dhillon, Horch, Hutchinson J.H.S. 2004

Do Residual Nerves Remain Viable After Amputation?



Residual Nerves Remain Viable After Amputation





Conclusion

Graded, distally referred, tactile and proprioceptive sensory feedback can be provided by intrafascicular stimulation of amputee nerve stumps.

Graded, distally referred, motor control signals can be obtained by intrafascicular recording from amputee nerve stumps.

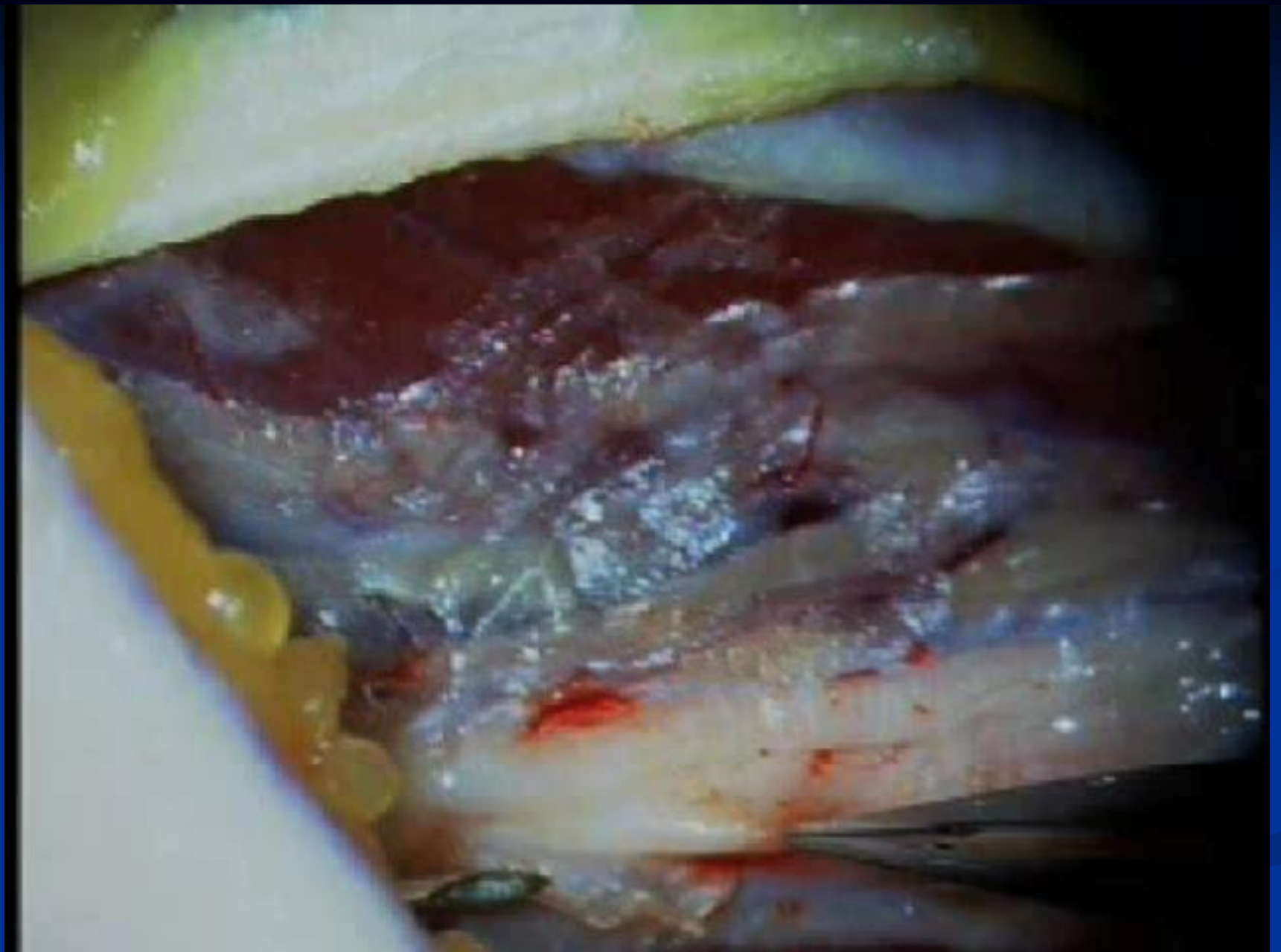
LIFES '08

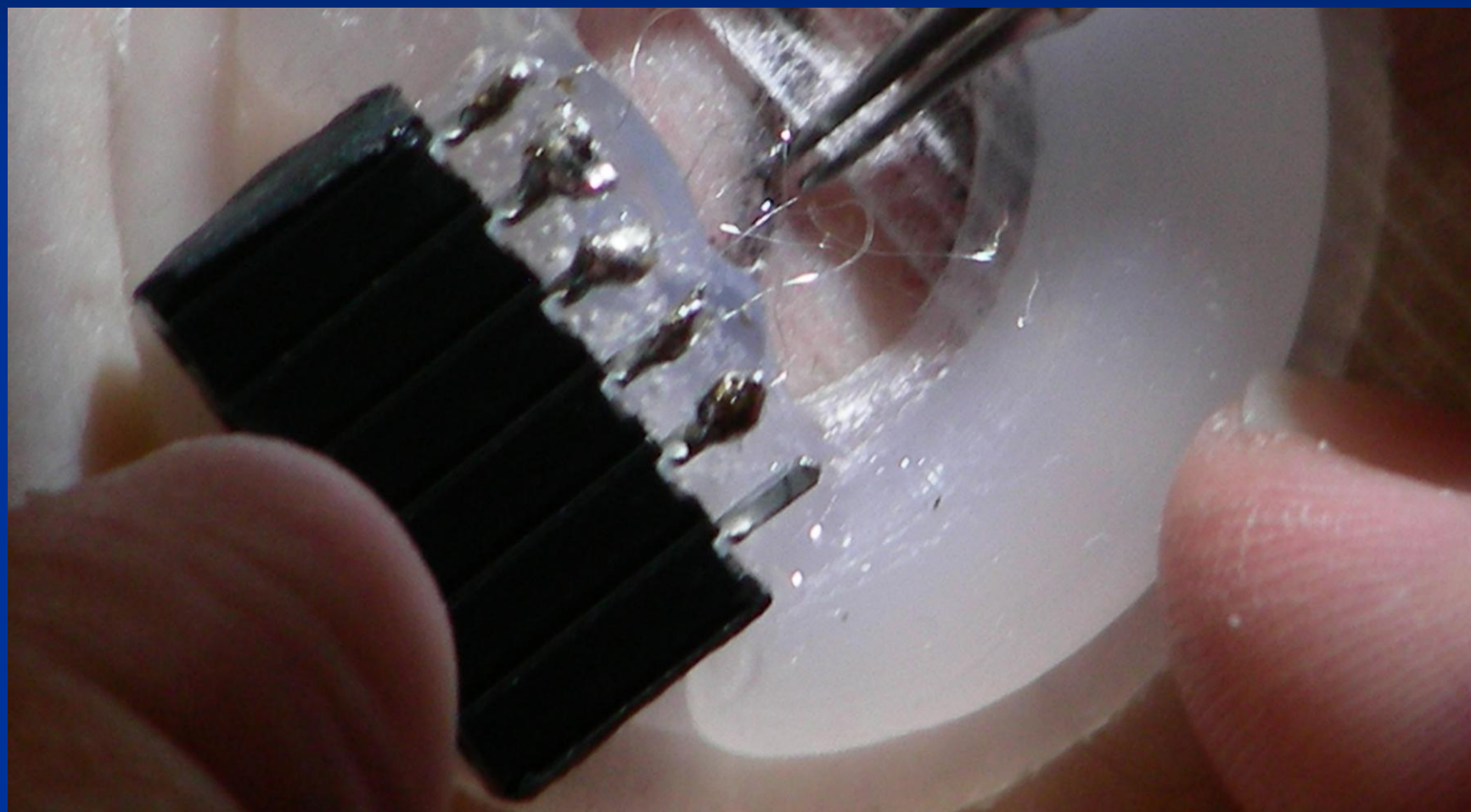
- NSF funded, IRB approved human volunteer experiments
- 1 incision, 2 electrodes in ulnar nerve, 4 in median nerve, just prox. to elbow
- 4 month chronic studies
- Sensation and motor output to prosthesis

2011

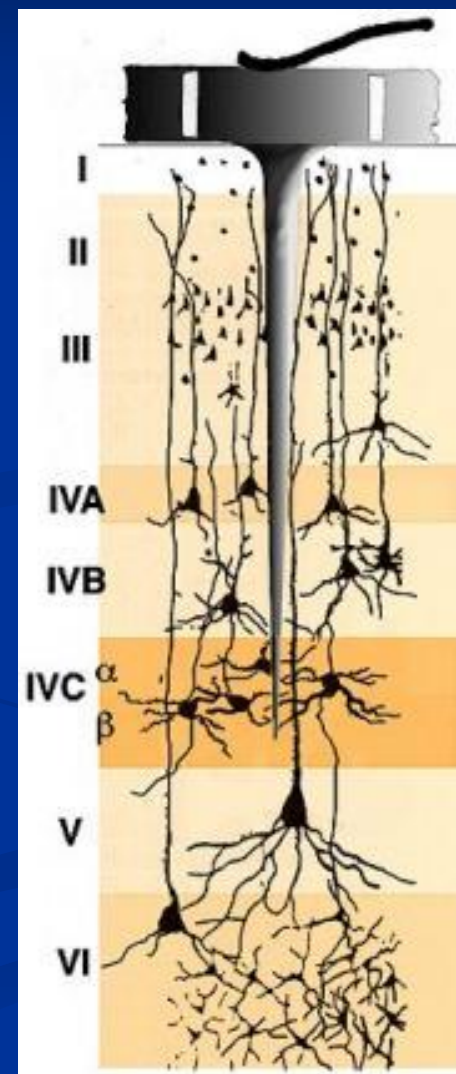








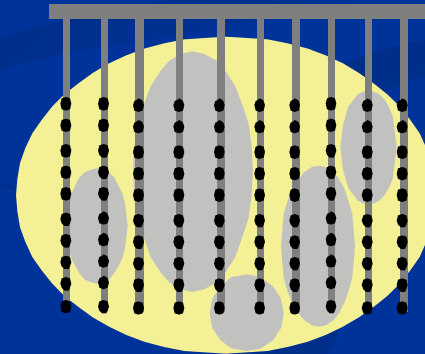
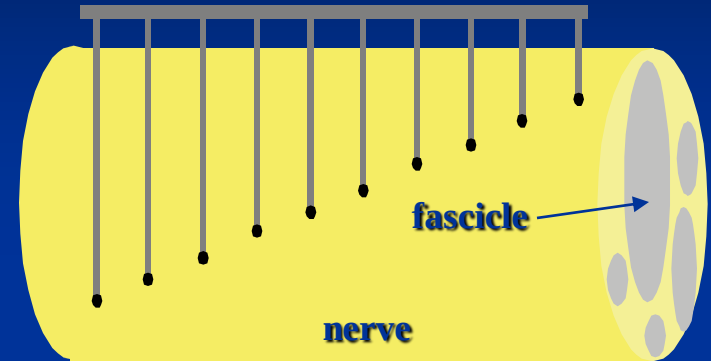
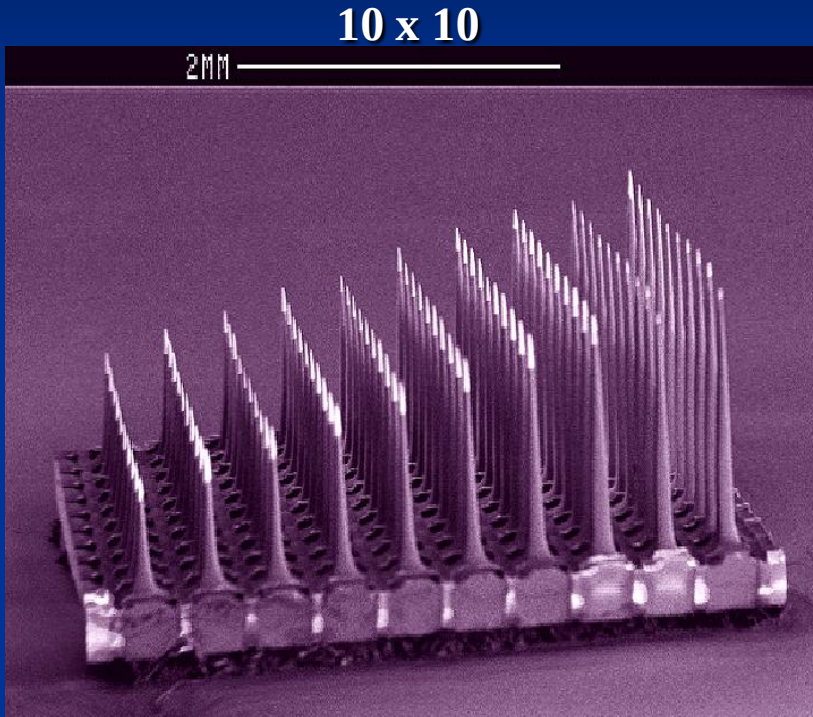
The Utah Electrode Array



Utah Slanted Electrode Array

Intrafascicular Multielectrode Stimulation (IFMS)

The Utah Slanted Electrode Array (USEA)



A neuroprosthetic “smart bomb”

- Proximity and selectivity: activates only selected nerve fibers
- Multi-site: can activate many different fibers independently

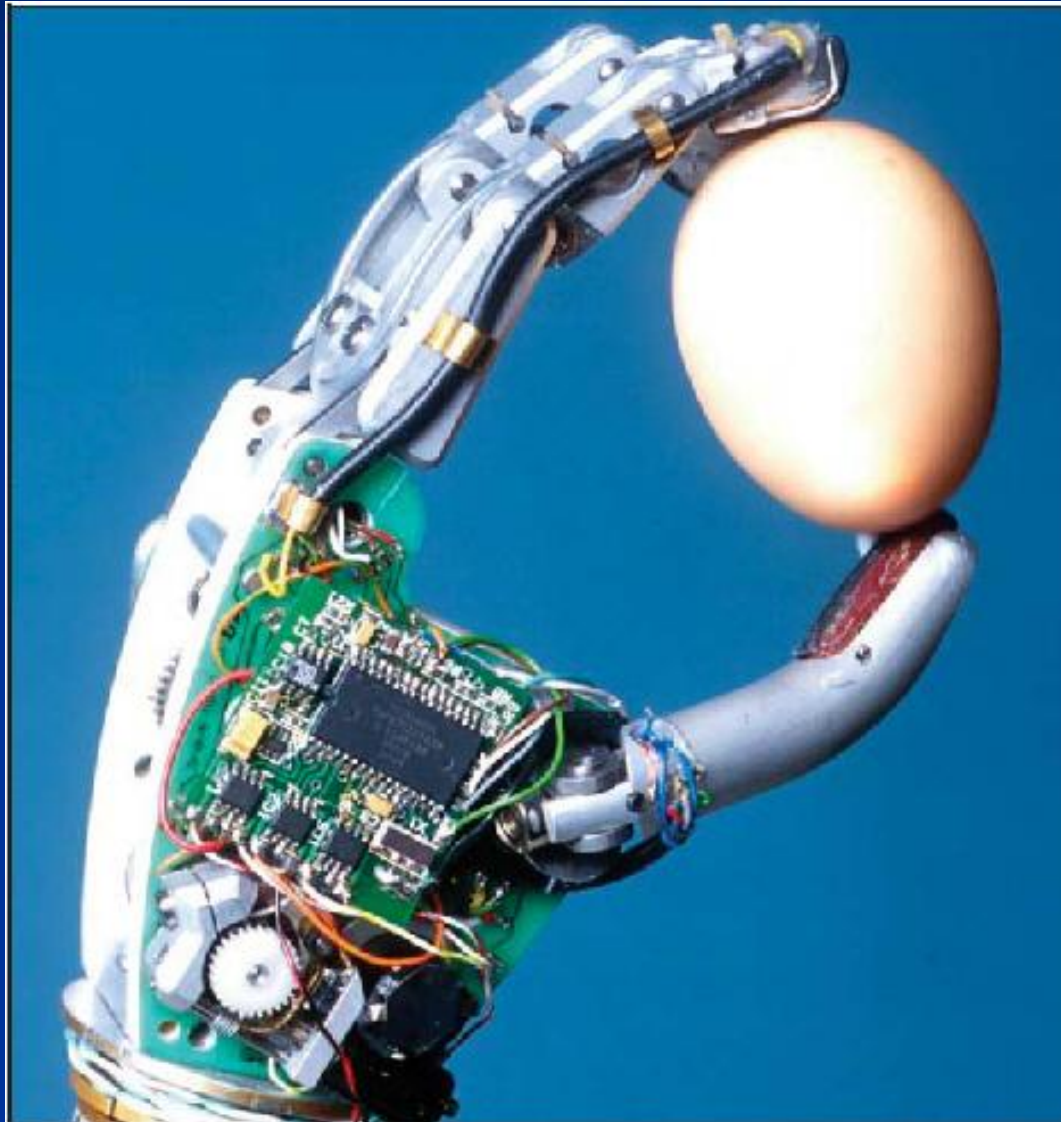
Enhanced, Selective Access to Multiple Muscles and Motor Units

B/TE	LG	LG	P	P	E	T/E	PB/T	PB/T	
B/TE	LG	LG	F	F		T/E	PB/T	PB/T	
B/TE	MG	LG	F	P		E	PB/T	PB/T	
	MG	LG	F	P	F	E	T/E	PB/T	PB/T
B/TE	MG	LG	P	F	F	E	T/E	PB/T	PB/T
B/TE	MG	LG	P	T	S	E	T/E	PB/T	PB/T
B/TE	MG	S	P	P	P	E	E	PB/T/E	PB/T
B/TE	MG	LG	LG	P	P	E	E	E/T	PB/T
B/TE	MG	LG	S	P	F	E	E	E	PB/T
B/TE	LG	S	S	S	F	F	E	PB/T	PB/T

B/TE = biceps femoris (thigh)
 PB = peroneus brevis
 MG = medial gastrocnemius
 LG = lateral gastrocnemius
 S = soleus
 F = flexor hallucis longus
 P = plantaris
 E = extensor digitorum longus
 T = tibialis anterior

- 9 different leg muscles selectively accessed via a single USEA implanted in cat sciatic nerve
- Between-muscle selectivity
- Within-muscle independence
- Low stimulation currents: 1-10 uA

Sensory Feedback



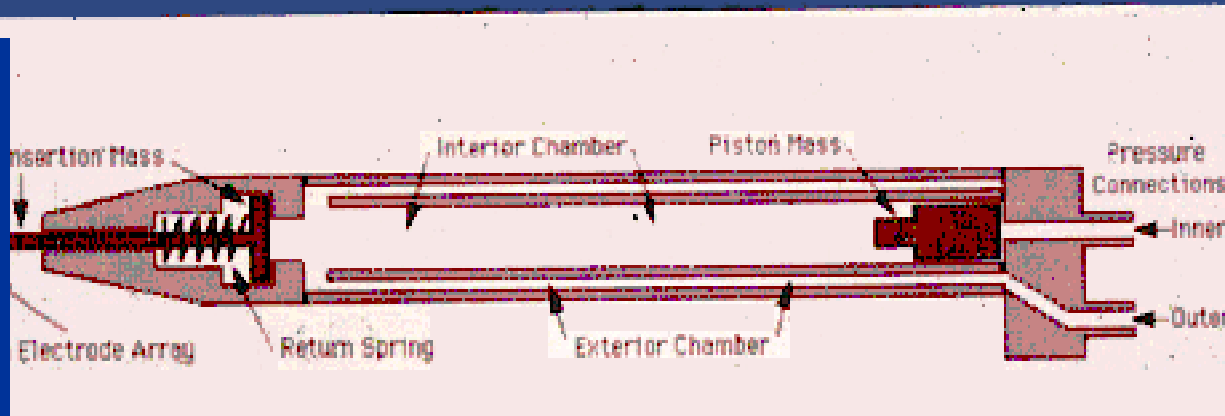
Surgical Implantation of Electrode Array

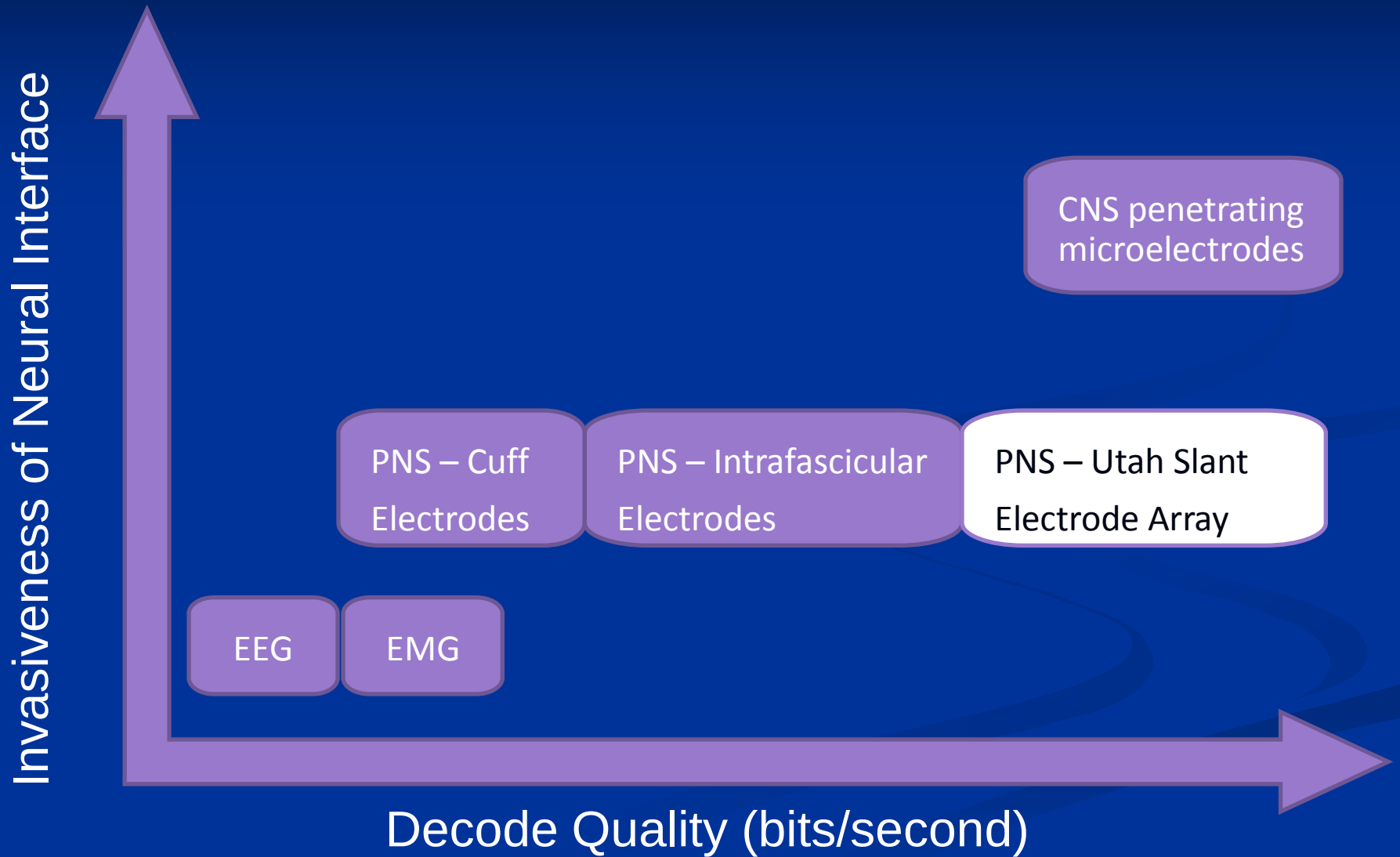
Automated, simple, reproducible

- “Plug & Play”, push-button operation
- A key feature for clinical implementation!
- 1 insertion = 100 electrodes
- < 200 usec (little tissue compression)



Impulse Inserter

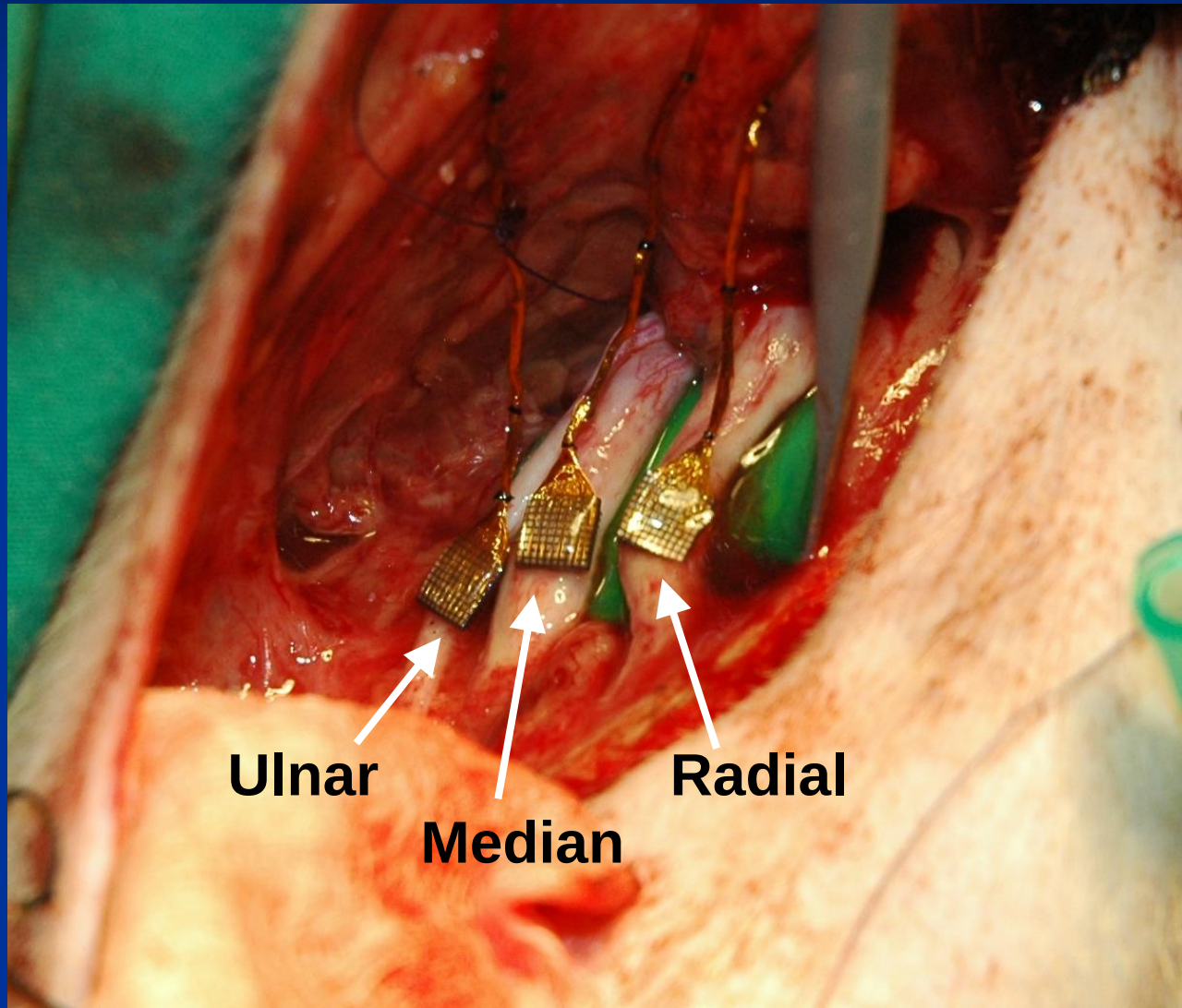




USEA Studies

- 2005-2008 Cat studies for DARPA/DOD
- 2008 “walking cat”
- 2009 Non human primate at Northwestern University

USEAs in 3 Arm Nerves of Non-Human Primate

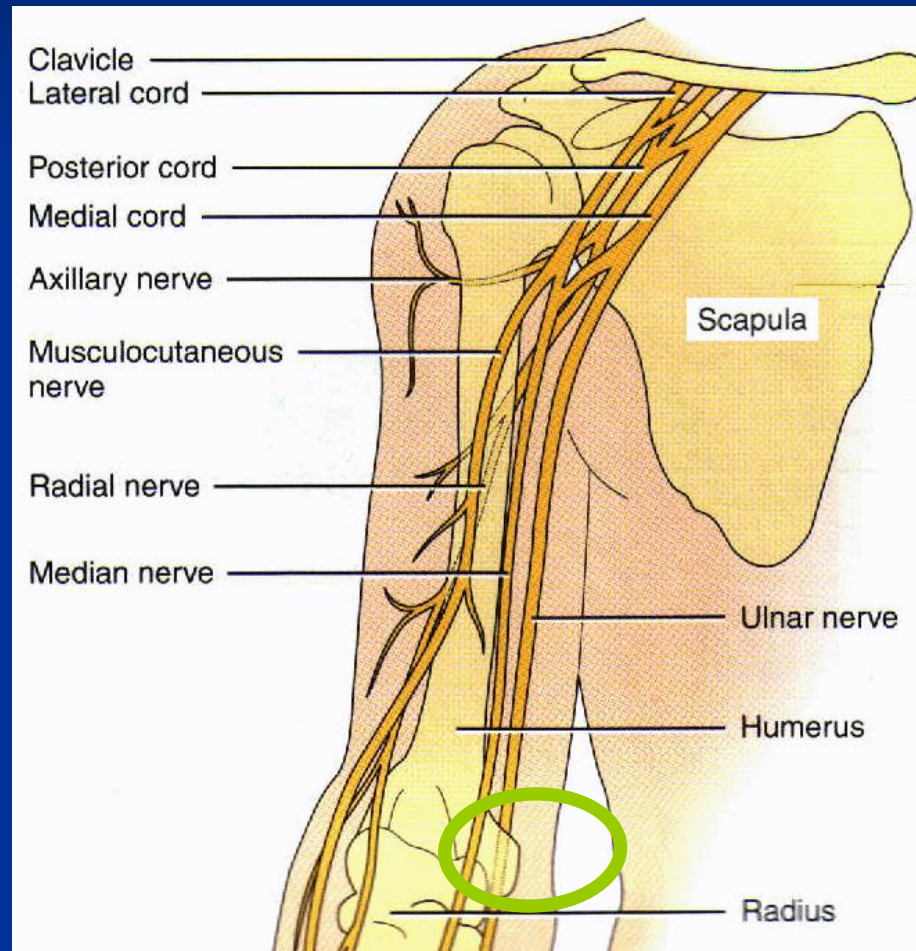


2-3 USEA implants

Radial (Ext.) and Median(Flex.)

Ulnar and Median ?

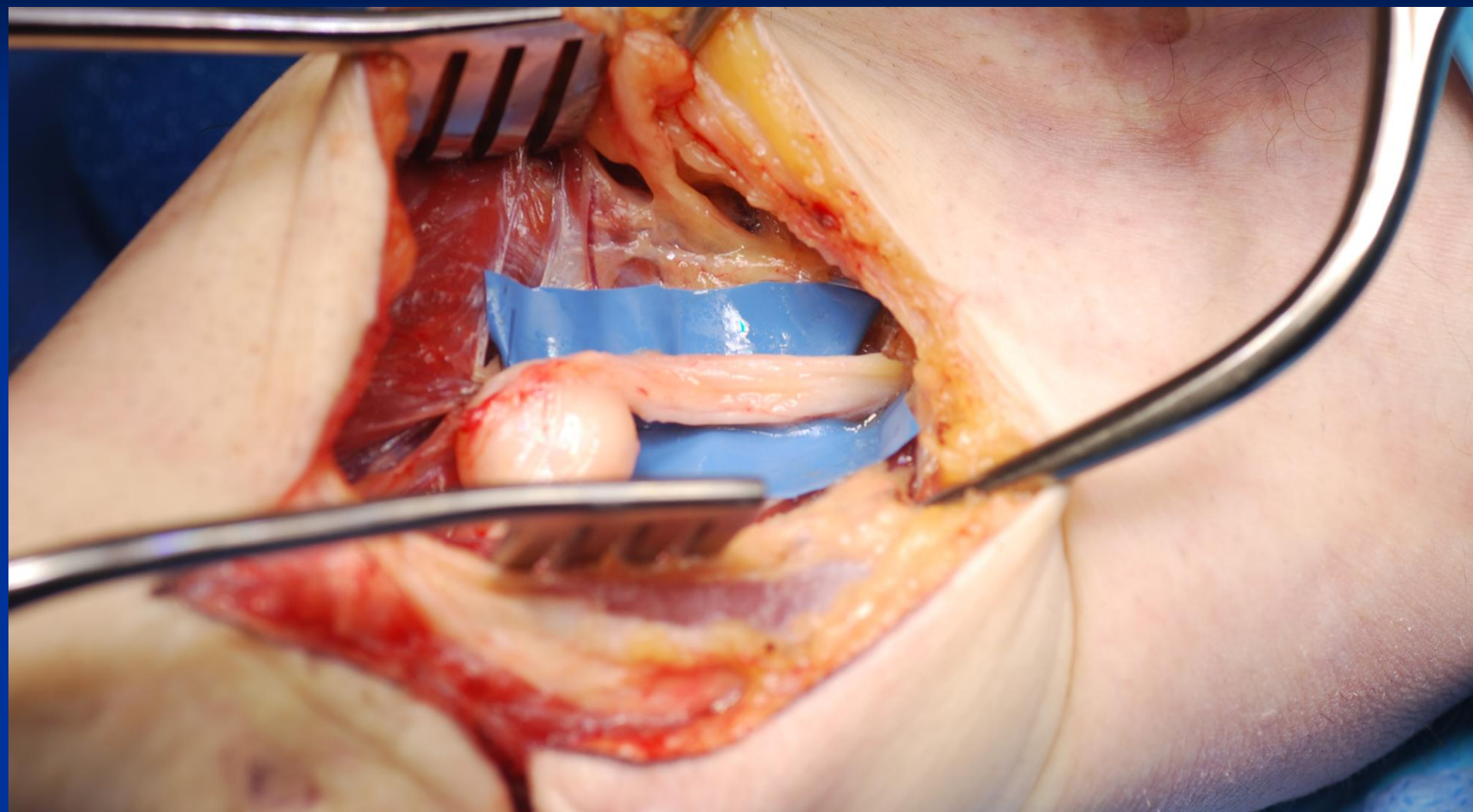
Ulnar only?



2012

- IRB approved Human studies
 - up to 1 month chronic implantation
 - nerve stump histology
 - still percutaneous
- Looking for volunteers!





Median nerve stump width 11.5mm

Chronic Human USEA Implant

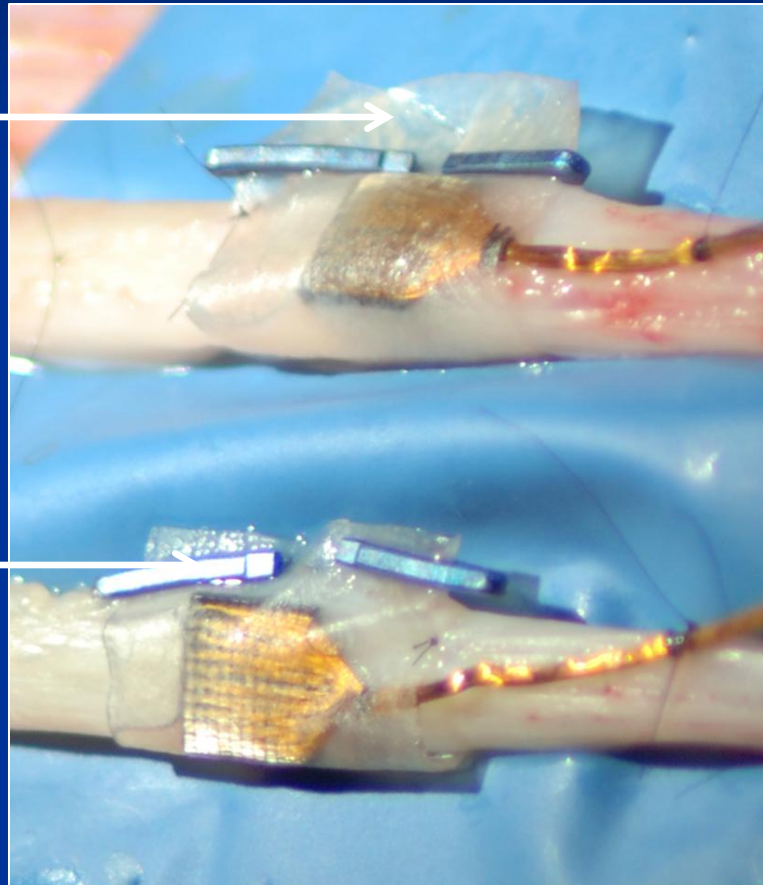


Trocar Surgical Method to Pass USEA to nerve

Acute Human USEA Implant: Lower Arm

Organic nerve wrap
for containment
system (AxoGen
Nerve Guard,
AxoGen Inc)

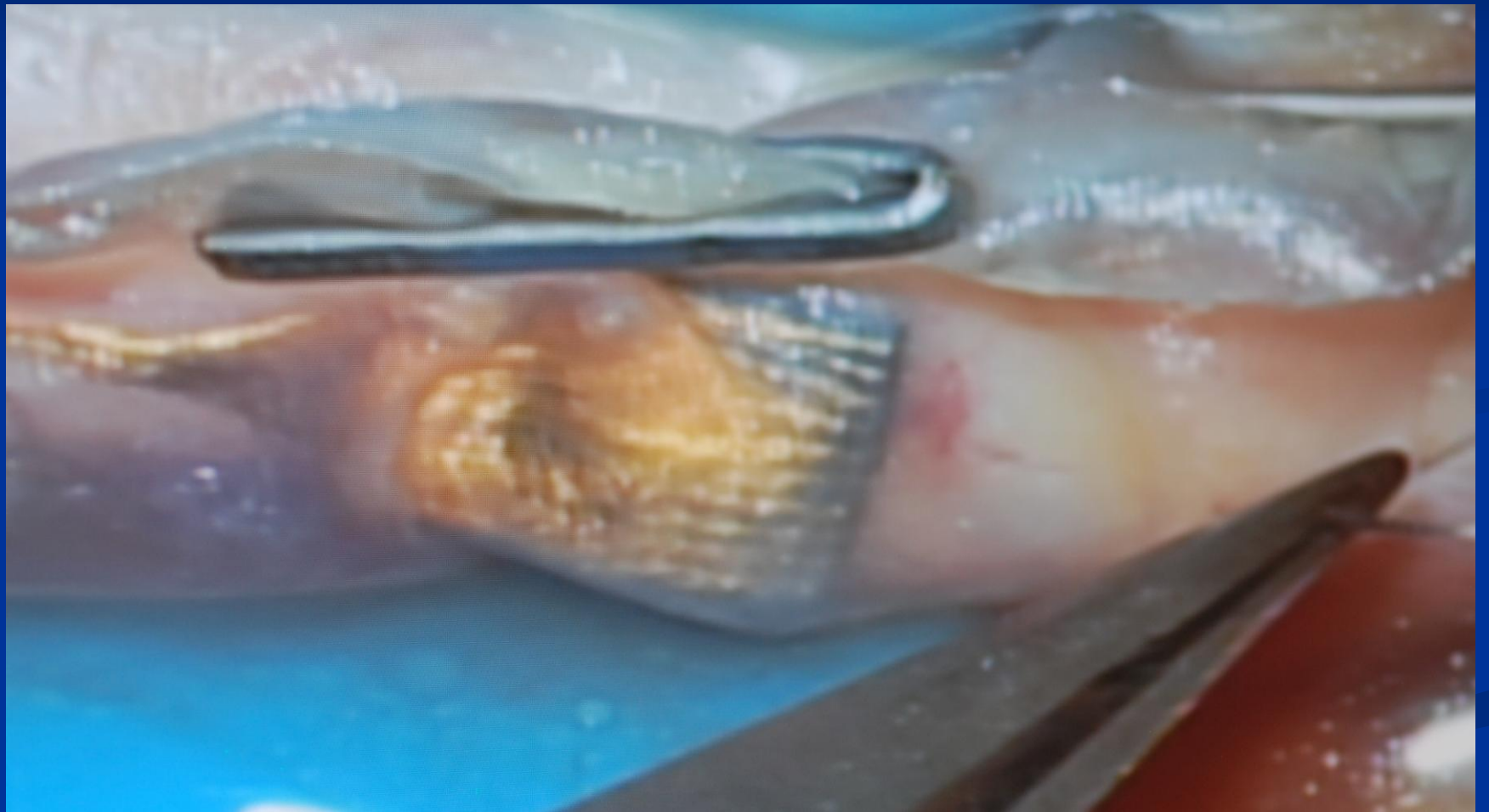
Vascular clips close
wrap



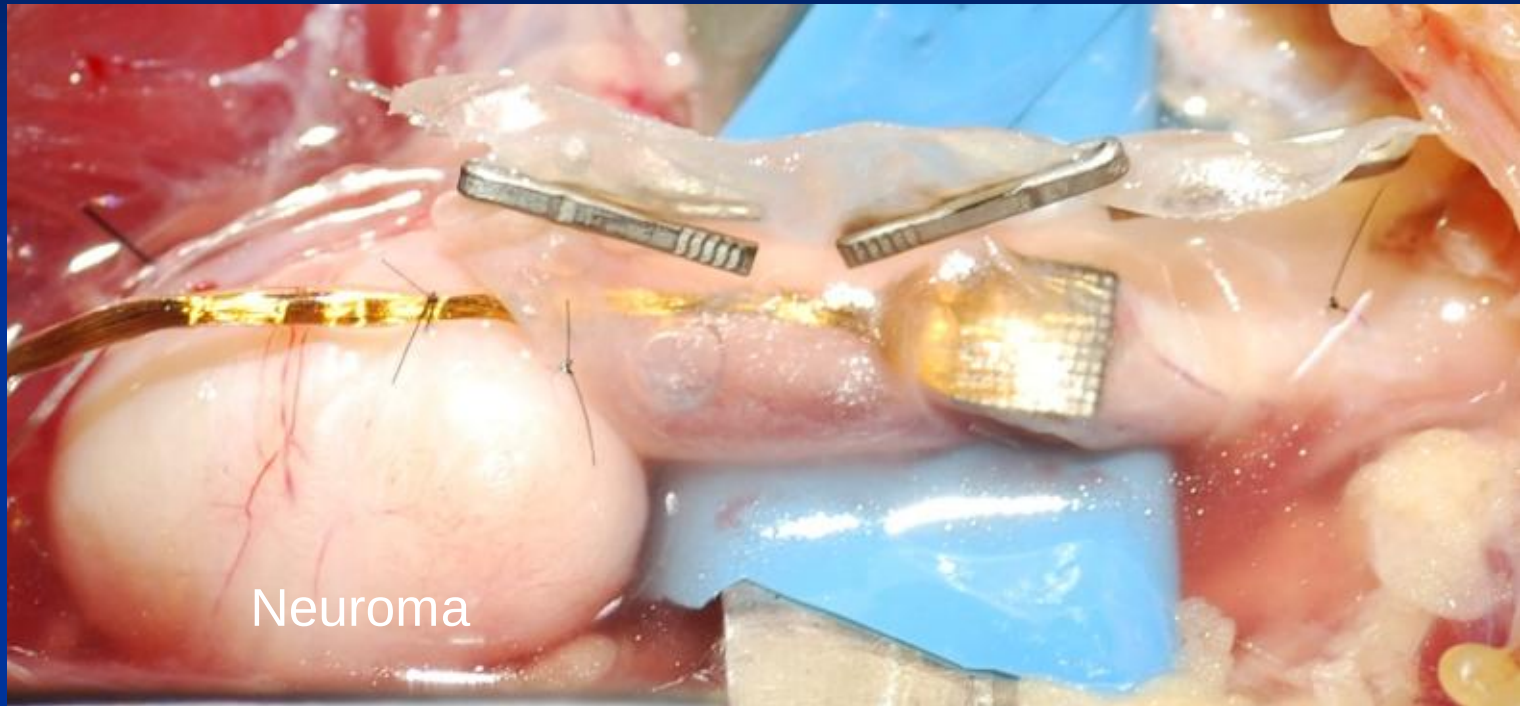
Median N.

Ulnar N.

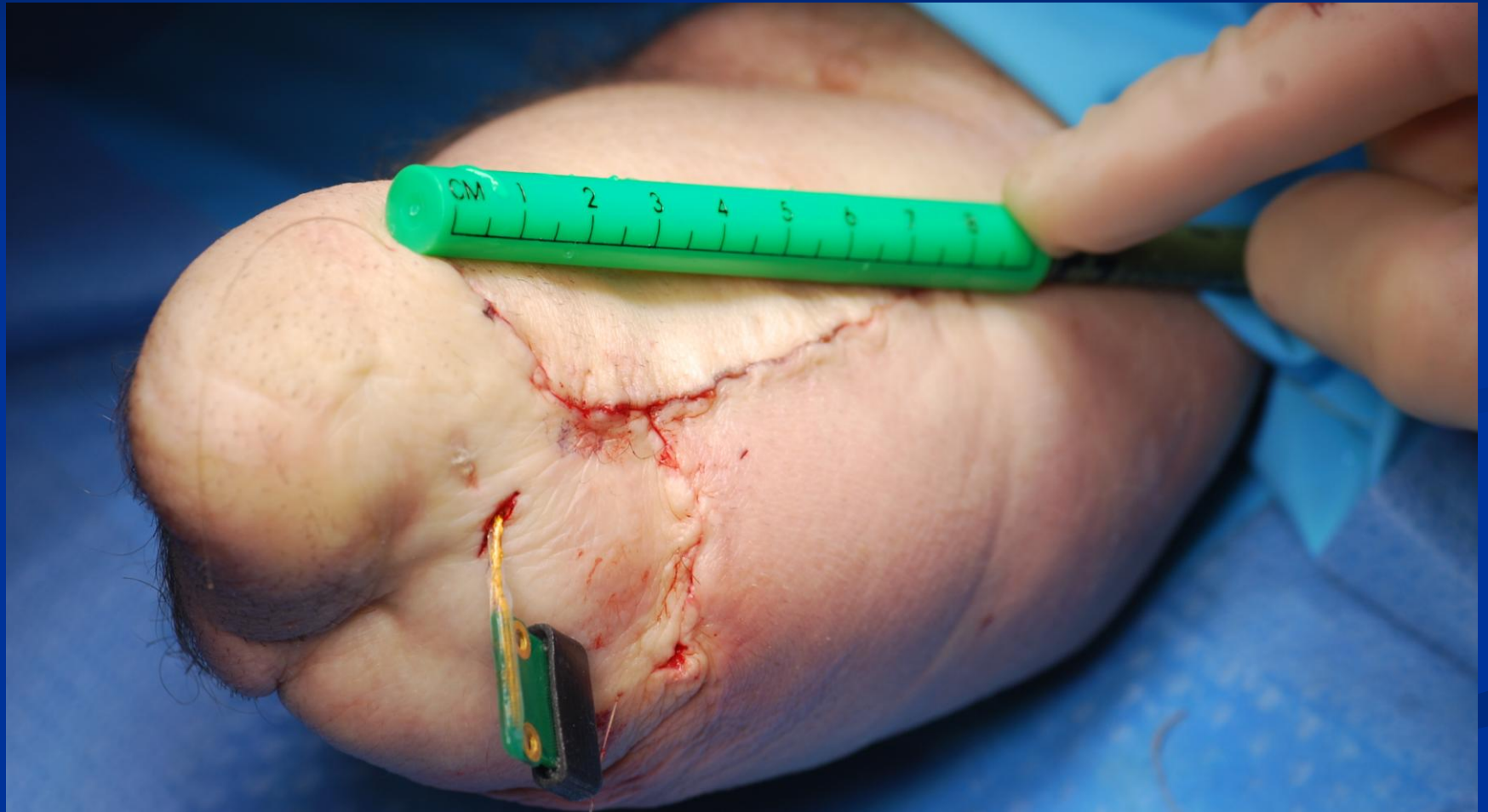




Chronic Human USEA Implant



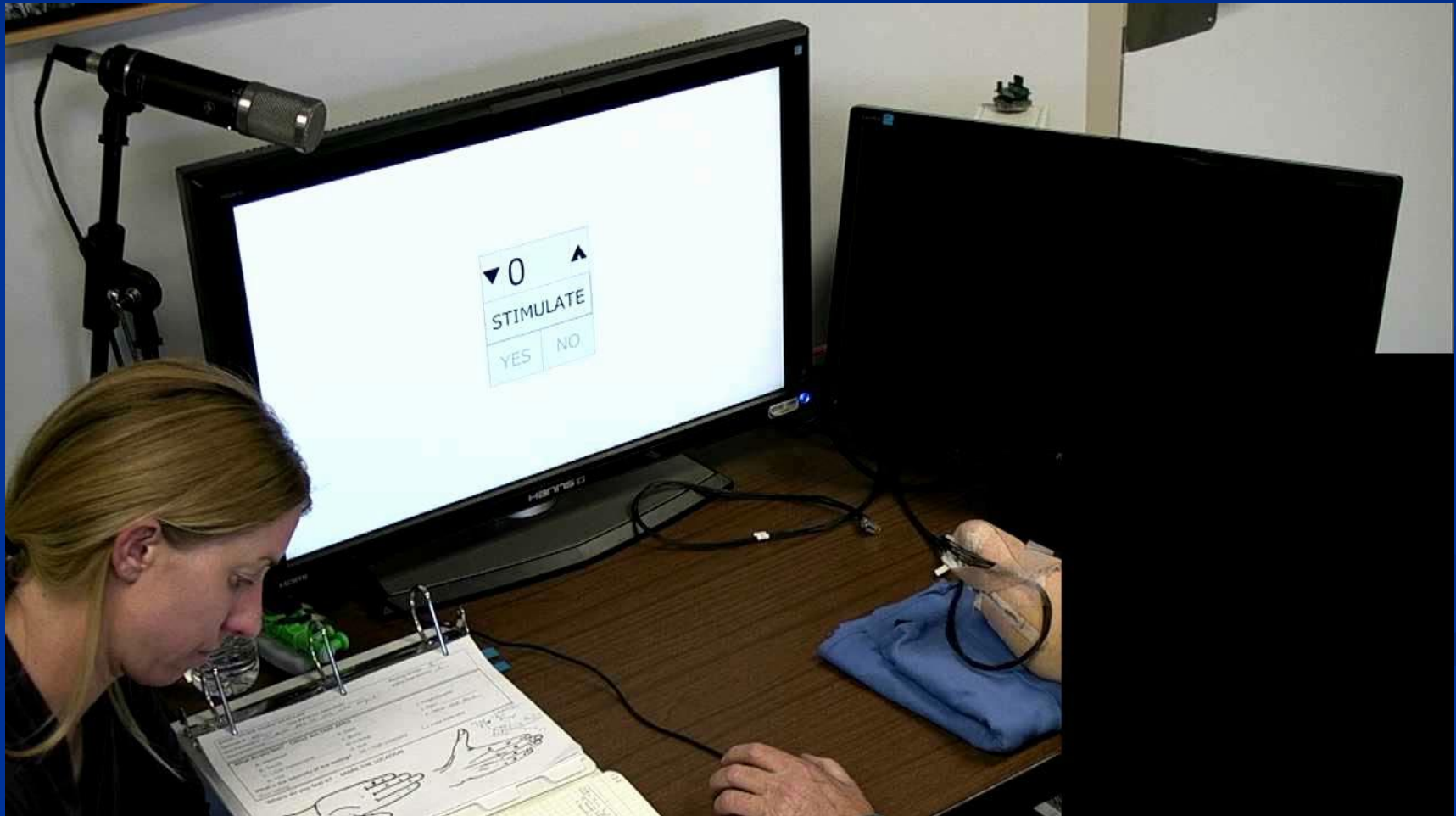
USEA implanted into median nerve and
contained with organic nerve wrap





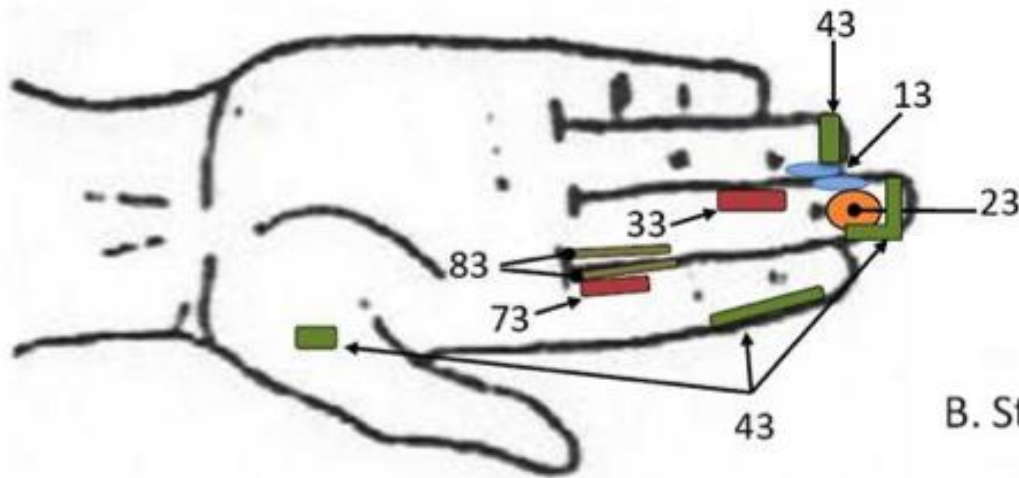
3. TA5 Sensory Feedback: Human peripheral nerve

- First evoked somatosensation using micro-stimulation via a USEA



Can stimulation evoke somatoensation?

A. Stimulation During One Session



B. Stimulation Over Time w/Same Electrode

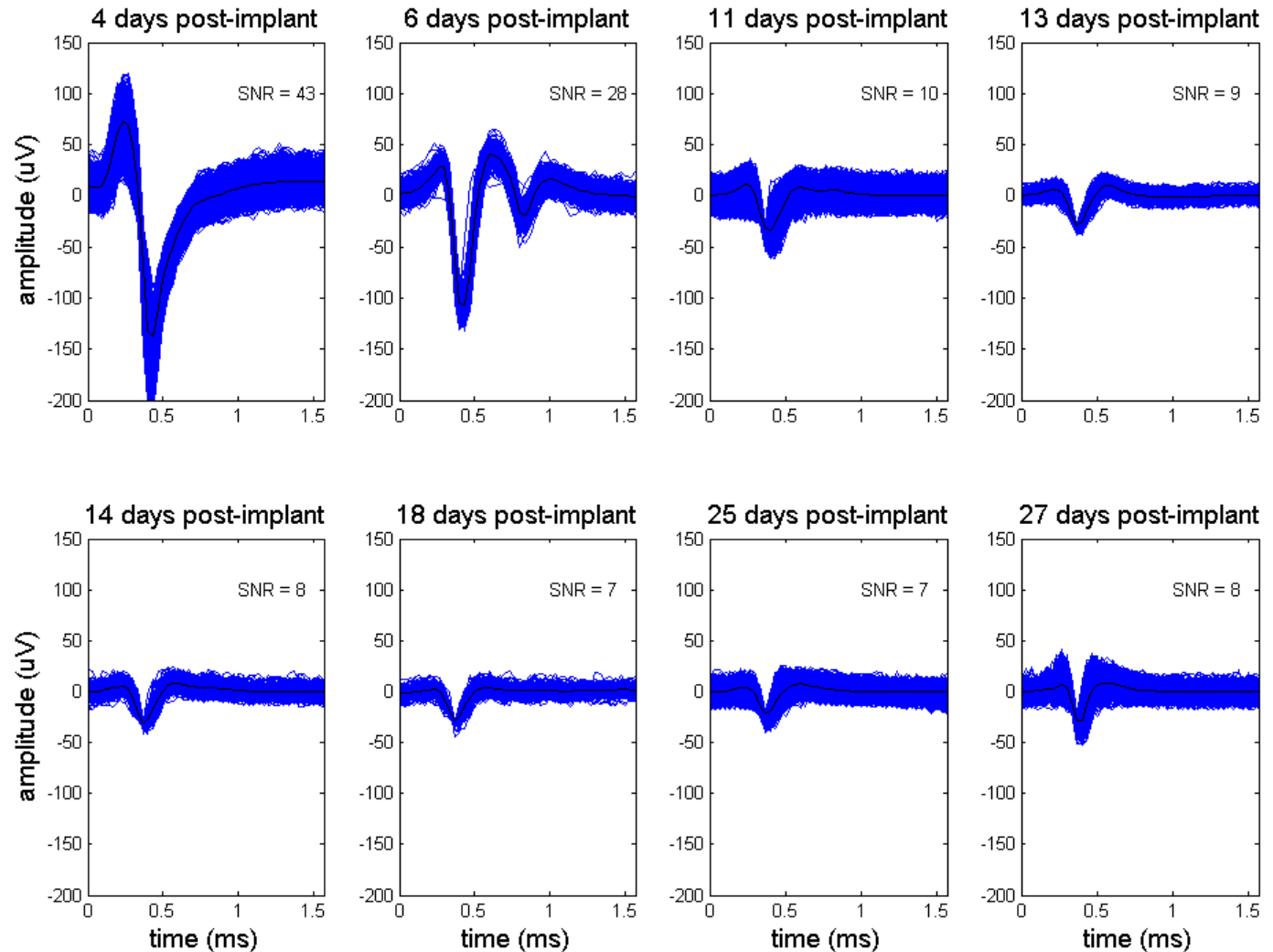


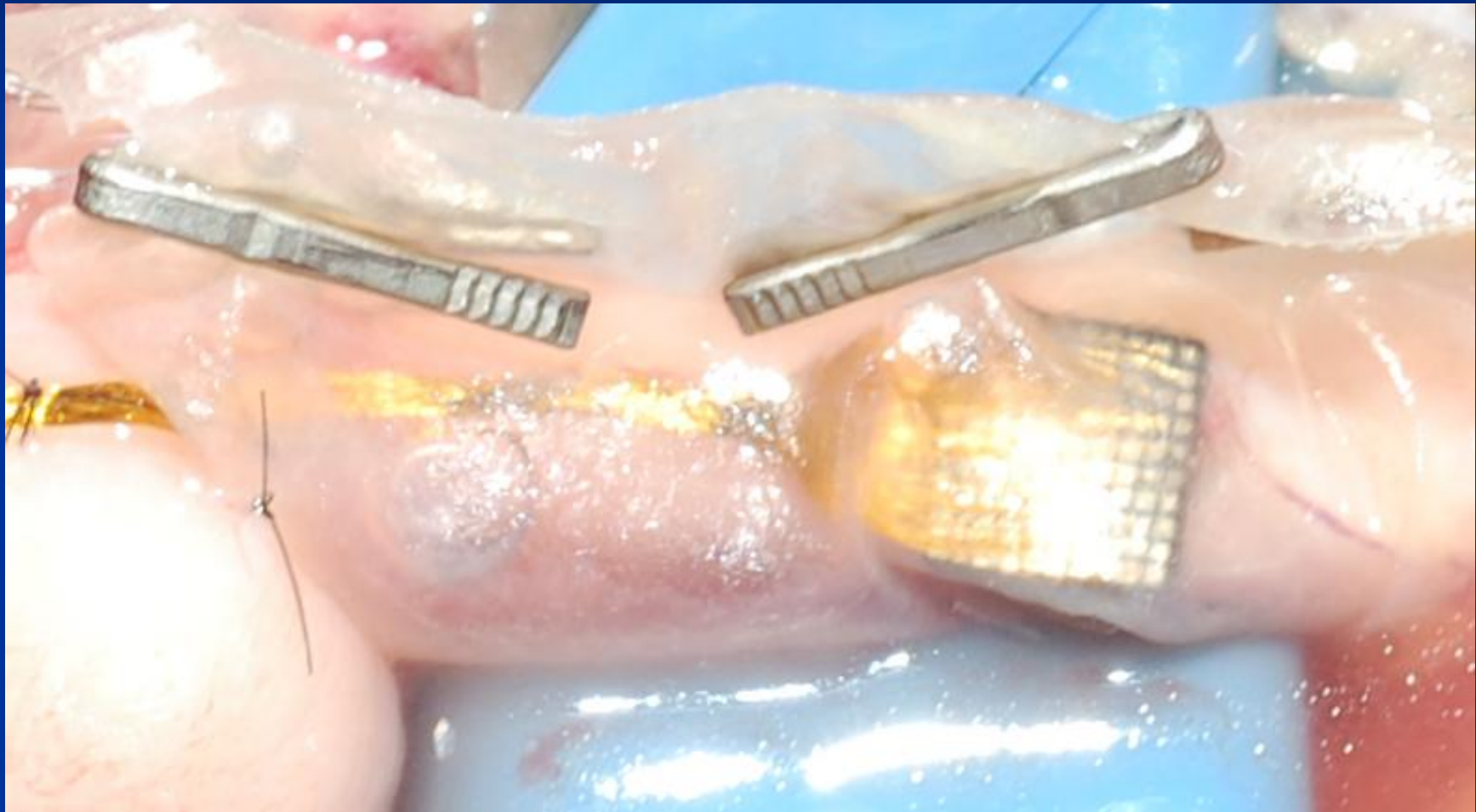
Electrode 19 Weeks 2-3
week 2, 11-14 (33uA) = blue circle
week 3, 11-19 (33uA) = red X
week 3, 11-21 (38uA) = red X

Yes!
Stimulation delivered via
single electrodes evokes
discrete percepts

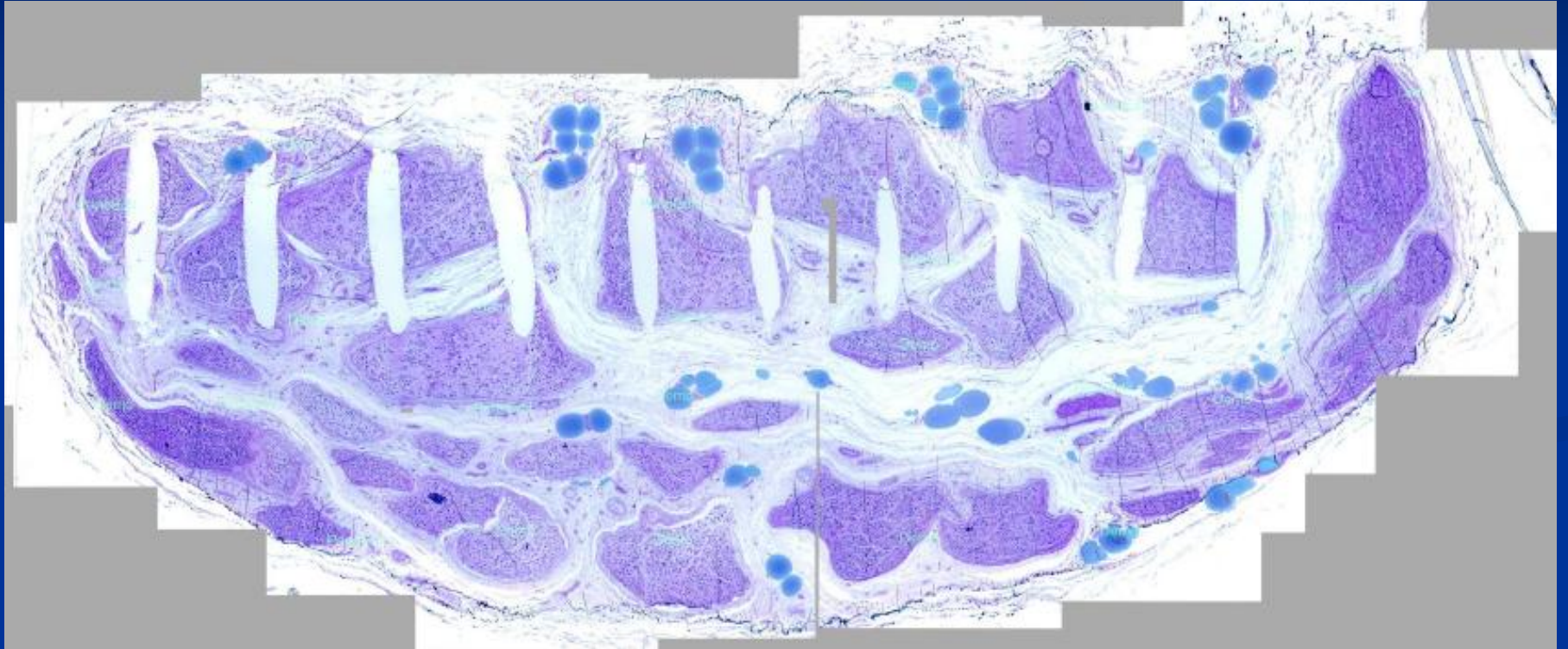
Can we record action potentials over time?

APs recorded
electrode 20
for 4 weeks





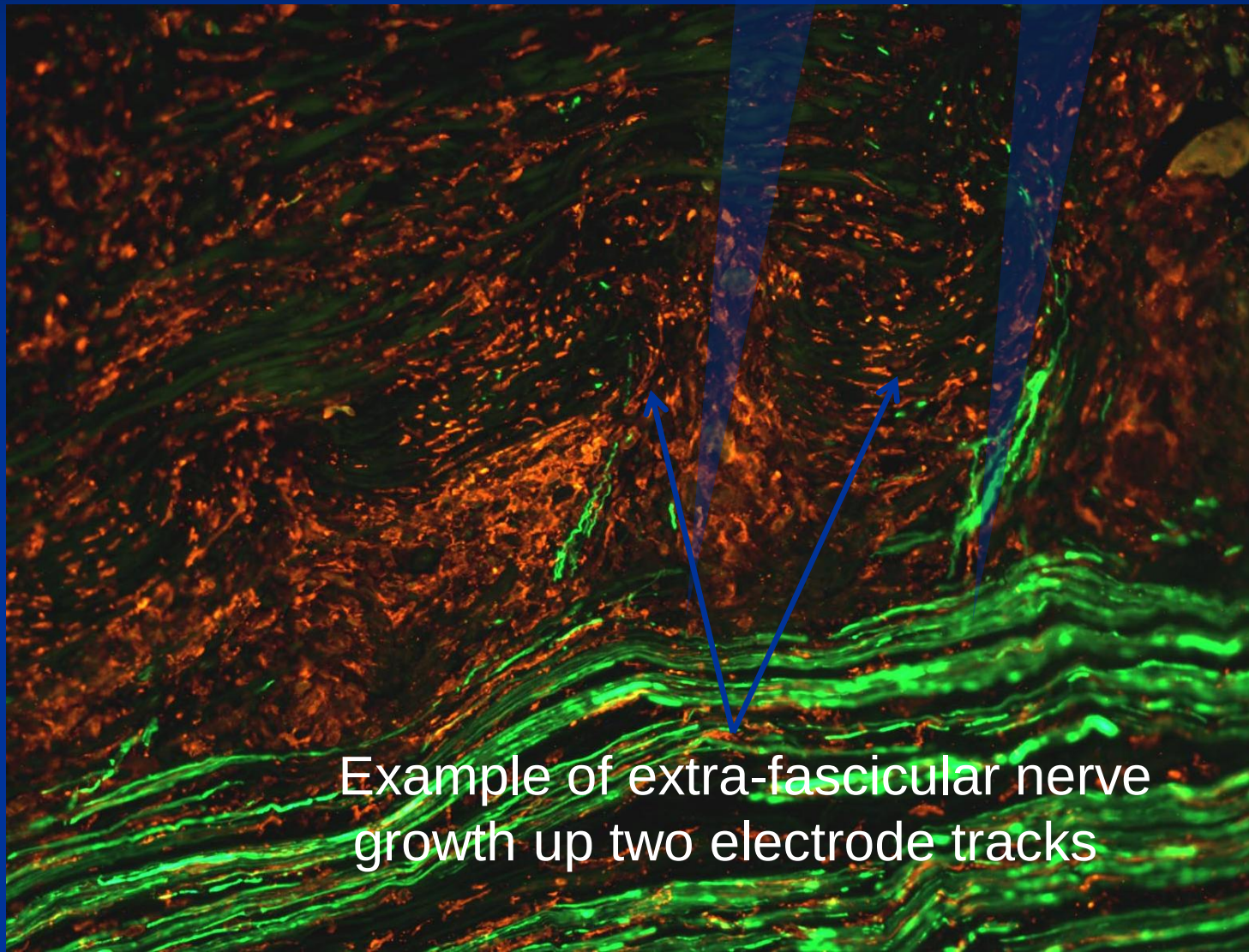
Histology



Median Nerve

Electrode tracks are seen across the nerve. Note: the section was not parallel to the electrode tracks so only part of the track is seen.

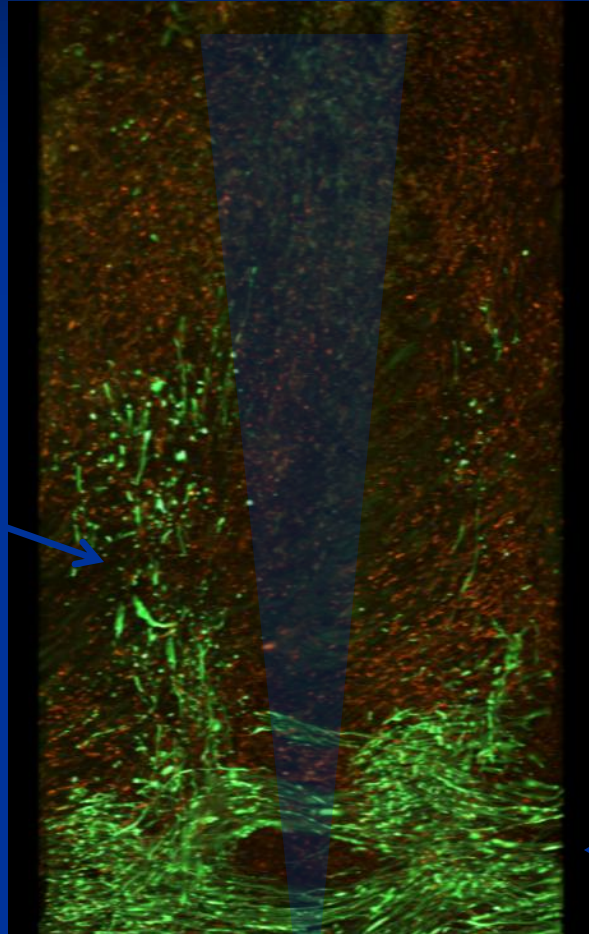
Human Histology



Example of extra-fascicular nerve growth up two electrode tracks

Antibody Staining of Electrode Sites

Extra-fascicular nerve growth



Nerve fascicle
(green = NF)

One USEA electrode
penetrating into a
fascicle

Advantages of Wireless Technology

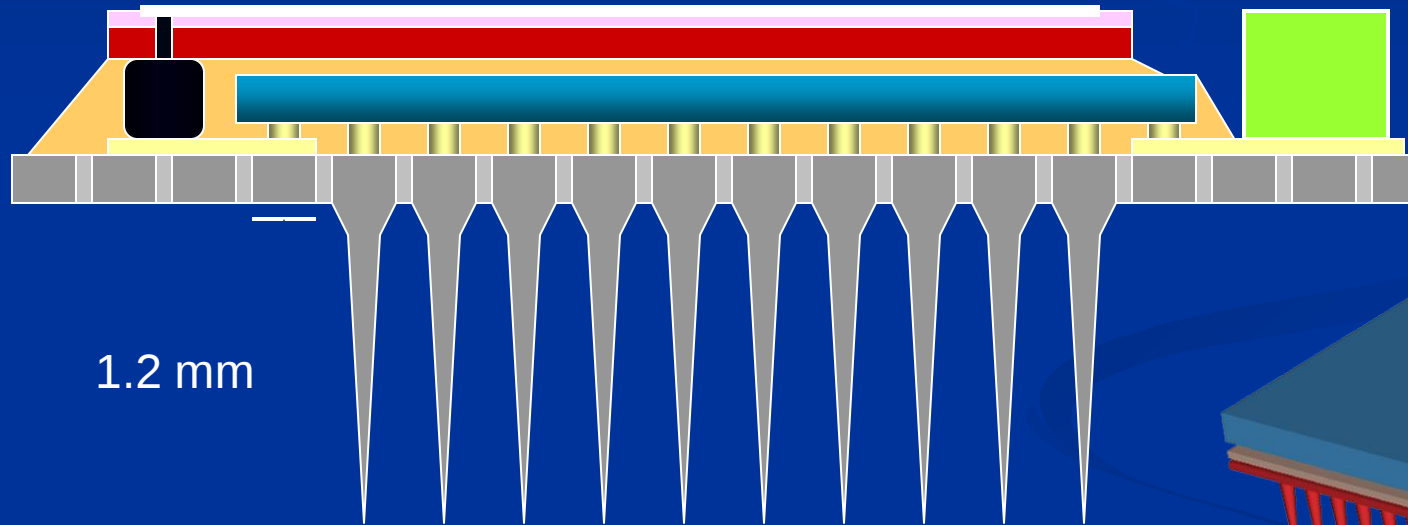
- Reduced risk of infection
- Reduced tethering forces
- Improved long-term recording/stimulation?
- Enhanced cosmetics

Integrated Neural Interface (INI)

Power receiving coil (Au)
on polyimide with ceramic
ferrite backing

Integrated circuit with neural
amplifiers or stimulation,
signal processing, and RF
telemetry electronics

SMD Capacitor
(0402 package)



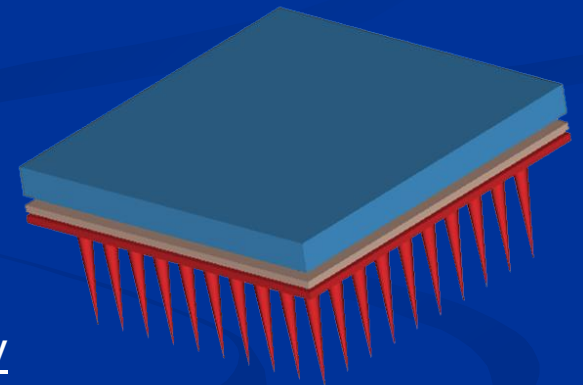
1.2 mm

400 μm pitch

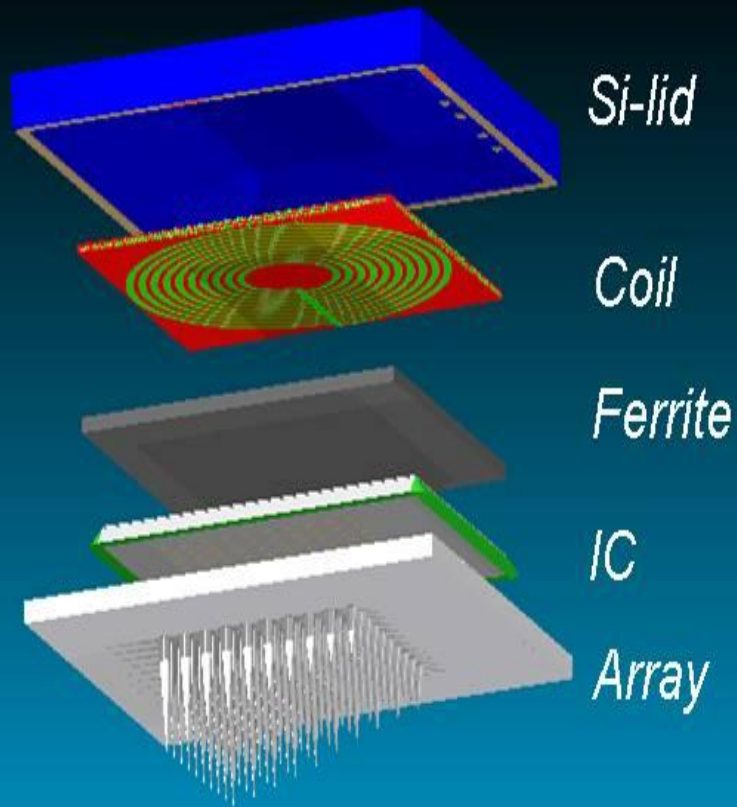
Entire assembly coated in
parylene and silicon carbide

Utah Microelectrode Array

Bulk micromachined silicon with platinum tips
and glass isolation between shanks



Integrated Wireless Recording Array



- Packaging & encapsulation
- Power coil
- Integrated circuit & SMDs
 - 100 Amplifiers
 - DSP
 - Telemetry
- Array electrodes

Summary

- Brain plasticity
- Chronic nerve stumps viable
- Improve mechanical arms
- Need better prosthetic interface
- Neural control
- Possibilities numerous
- Americans need to study Geography!



Future

- Verify functionality in humans long term
- Determine best surgical fixation procedure and instrumentation
- Verify appropriate histology of residual nerve
- Finalize wireless technology
- Osseous integrated interface without infection
- Put it all together!

Congenital Amputees?

- Nerve availability?
- Brain adaptability?
- Bilaterality?



Neuropathic Pain

- Giving 'normal sensation' to the peripheral nerve may mask/eliminate abnormal pain pathways
- Better than spinal column stimulators?
- Better than neurontin/lyrica?

Birth Plexus Palsy

- Keep muscles working while recovery occurs in first 6 months
- If recovery not proceeding then bypass injury site electronically
- Perhaps place electrodes at time of grafting
- Avoid need to graft?

Cerebral Palsy

- Utilize normal peripheral nerves and muscles controlled by other arm or normal half of brain?
- Would simple afferent or efferent stimulation decrease spasticity?
- Eliminate botox and baclofen?

Acknowledgements

Animal Studies

- UU Faculty
 - R Normann, B Greger, G Clark
 - D Hutchinson, P House, K Horch,
 - S Meek
- MD/PhD student
 - H Wark
- Postdoctoral Fellow
 - D Warren
- Graduate Students
 - N Ledbetter, S Towns, J Perry, K Gunalan, B Dowden, A Wilder, S Hiatt, J Baker, B Christensen
- Technicians
 - R Macchione, Q Ruan, K Nelson, T Taylor
- Northwestern U. Med. School
 - L Miller, J Ko, C Ethier, E Oby

Wireless Recording & Stimulation

- Chip Development
 - Reid Harrison et al.
- System Integration & Encapsulation
 - Florian Solzbacher et al.

External Interface (Beltpack)

- Shane Guillary et al.; Ripple, LLC

VIE

- Loeb et al., USC
- Beaty, Bishop et al., JHU-APL

IMES

- Weir, Troyk, Schorsch et al.; RIC & Sigenics

Funding

- DARPA BAA 05-26 (Neuroprosthetic arm; GC)
- R01-NS039677 (SCI, nerve stim for stance; RN)
- HHSN265200423621C (Wireless Cx array; FS)
- R01-NS053603 (LM)



THANK YOU!



The University of Utah

Department of Orthopaedics





Department of Bioengineering

Decoding Individuated Finger Flexions with Implantable MyoElectric Sensors (IMES)

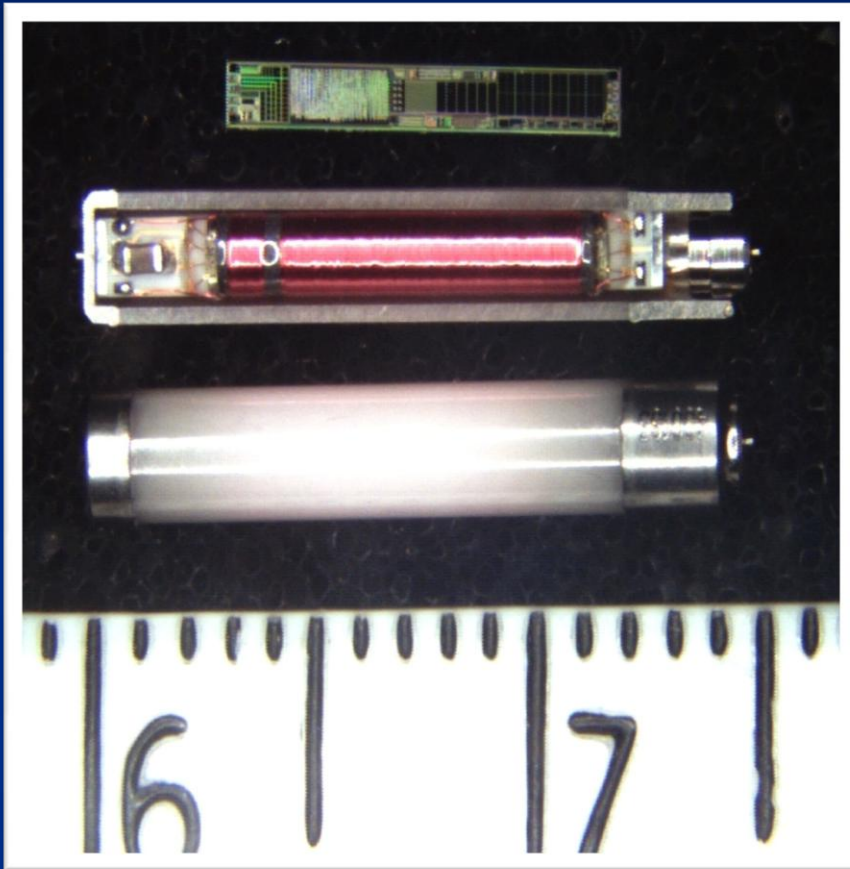
Justin J. Baker¹, Dimitri Yatsenko¹, Jack F. Schorsch², Glenn A. DeMichele³, Phil R. Troyk⁴, Douglas T. Hutchinson¹, Richard F. ff. Weir², Gregory Clark¹, and Bradley Greger¹

¹University of Utah ²Rehabilitation Institute of Chicago ³Sigenics Inc.

⁴Illinois Institute of Technology

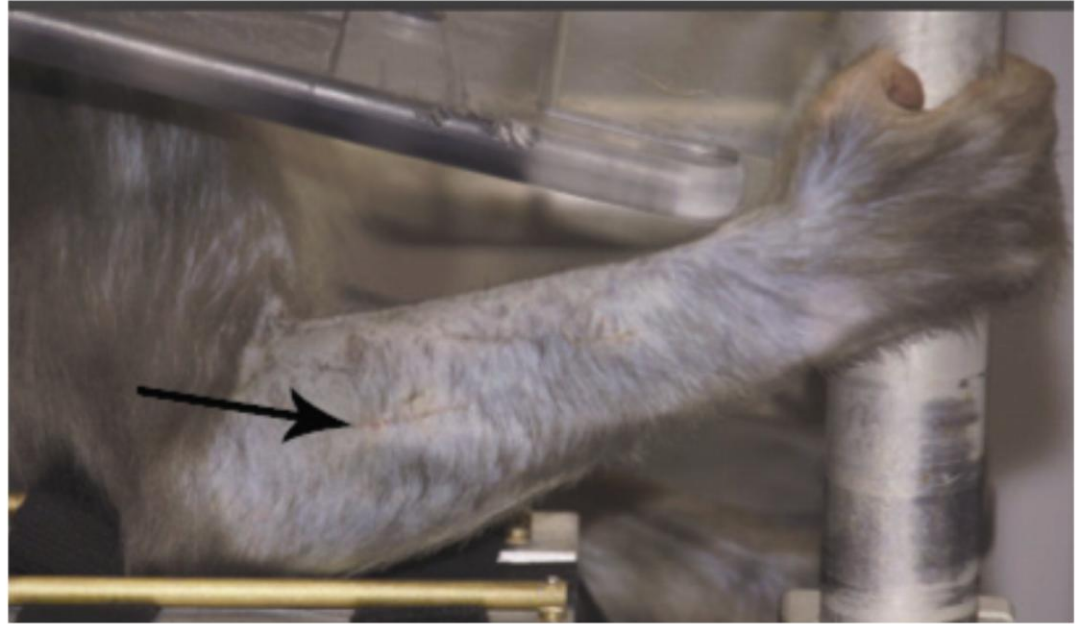
30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society

August 20-24, 2008



- Transmits and receives EMG signal wirelessly
- 15 x 2 mm

IMES IMPLANTATION



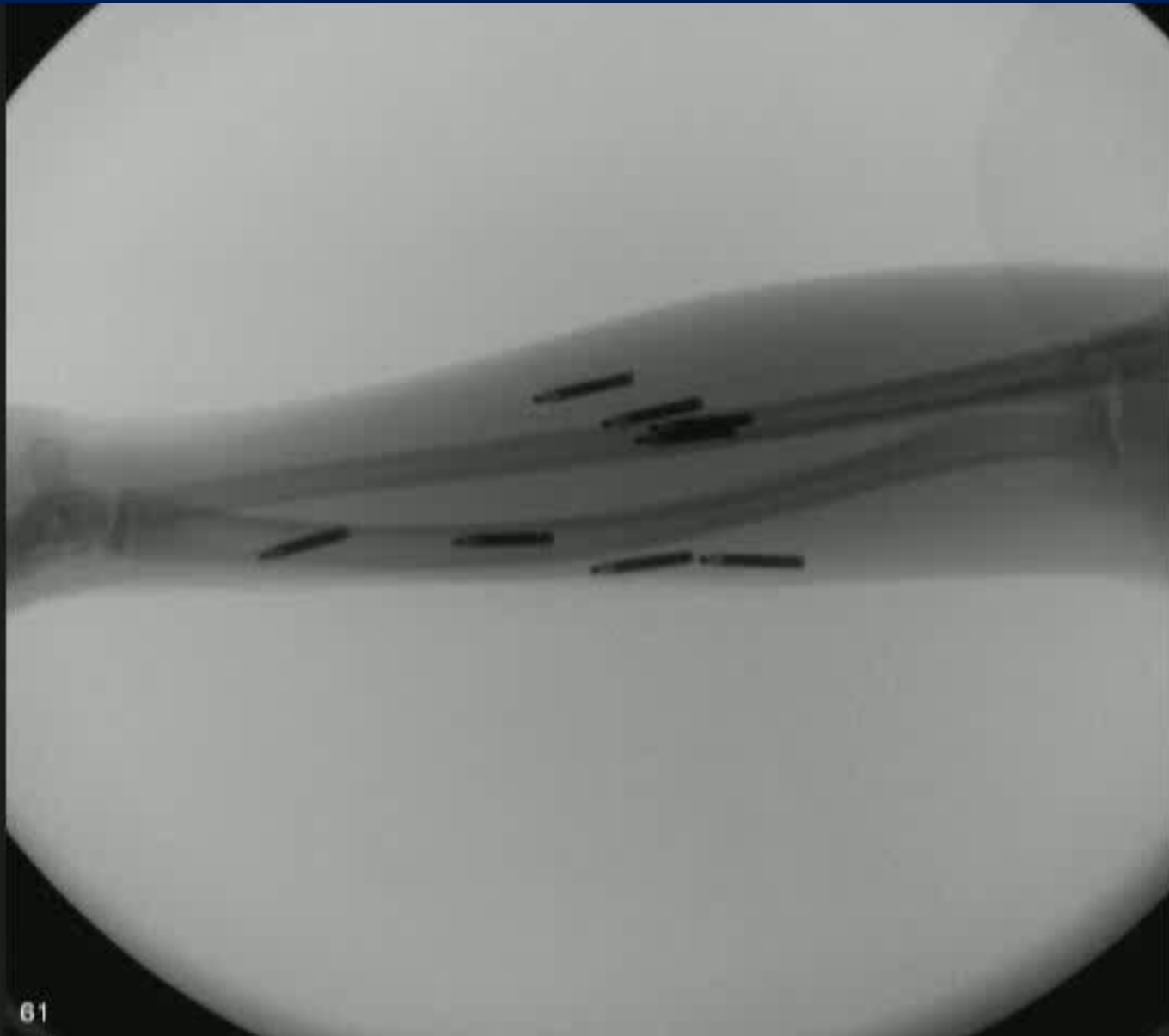
IMES LOCATION + FUNCTION



Muscles where IMES were implanted and their function

FDP-deep	Flex index (#2)
FDP-superficial	Flex #3,#4,(#1- if 3 + 4 are flexed)
FDS	Flex middle finger (#3)
FCr	Wrist flexion
APL	Thumb abduction
EDCI	Extension of #4,#5
EDC	Extension of #2,#3
Wrist extensor	Wrist extension
Thenar eminence	Thumb flex

IMES: REAL TIME X-RAY VIDEO

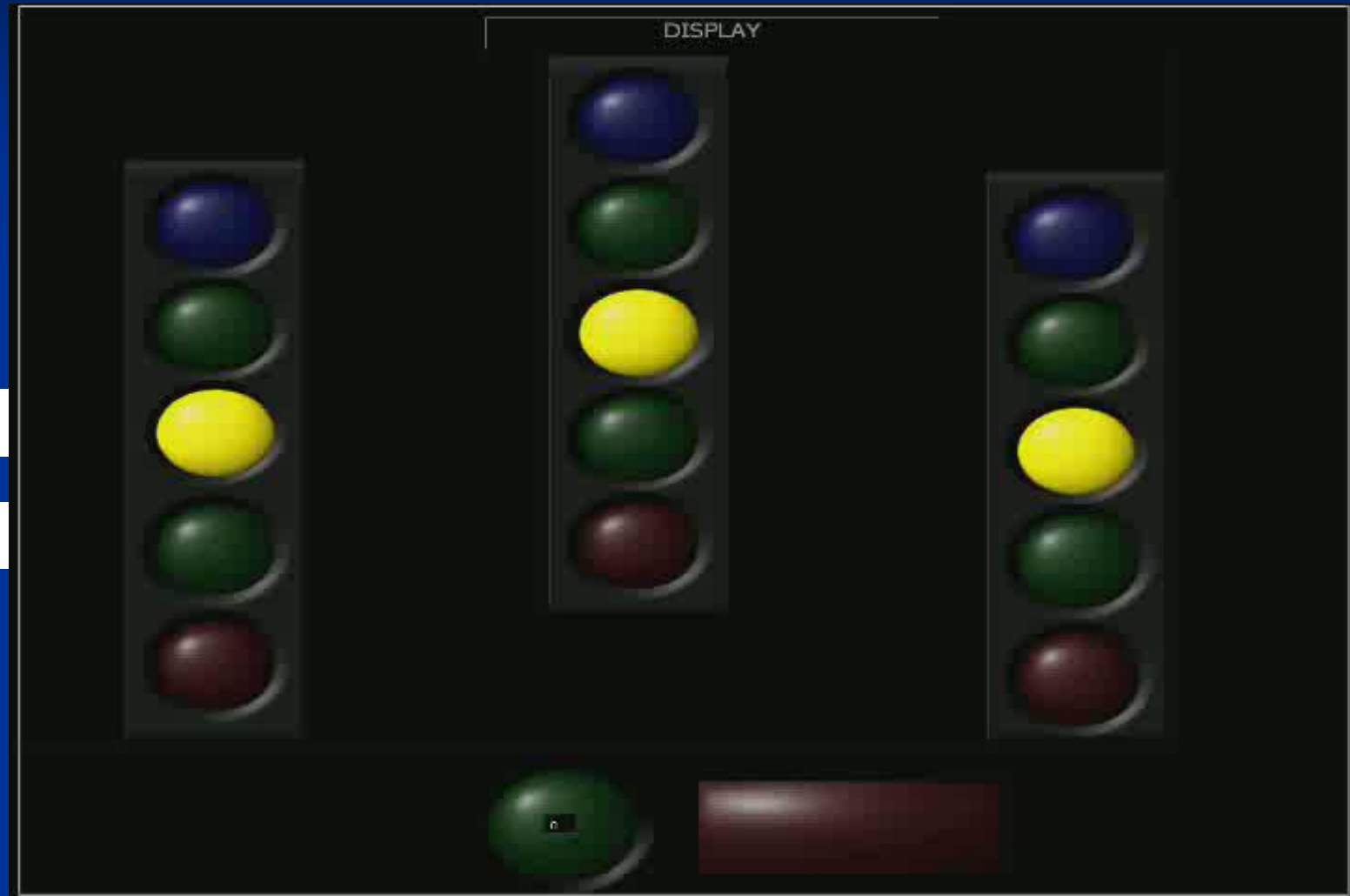


THE BEHAVIORAL TASK

THUMB

INDEX

MIDDLE

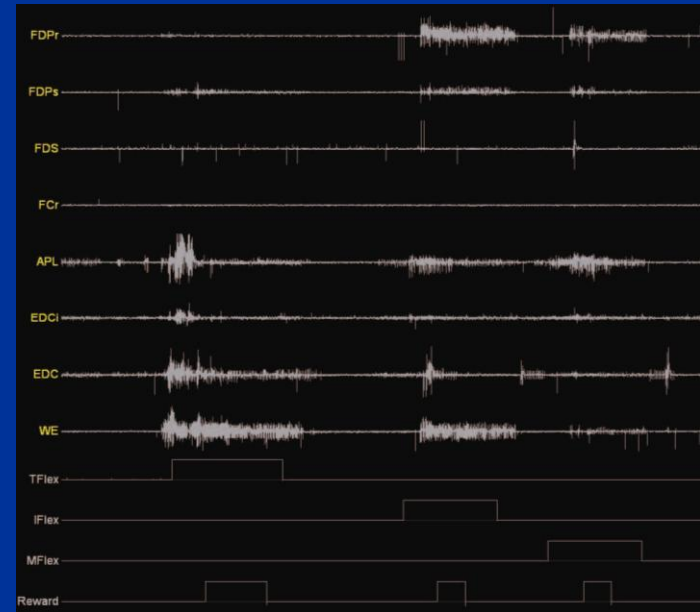
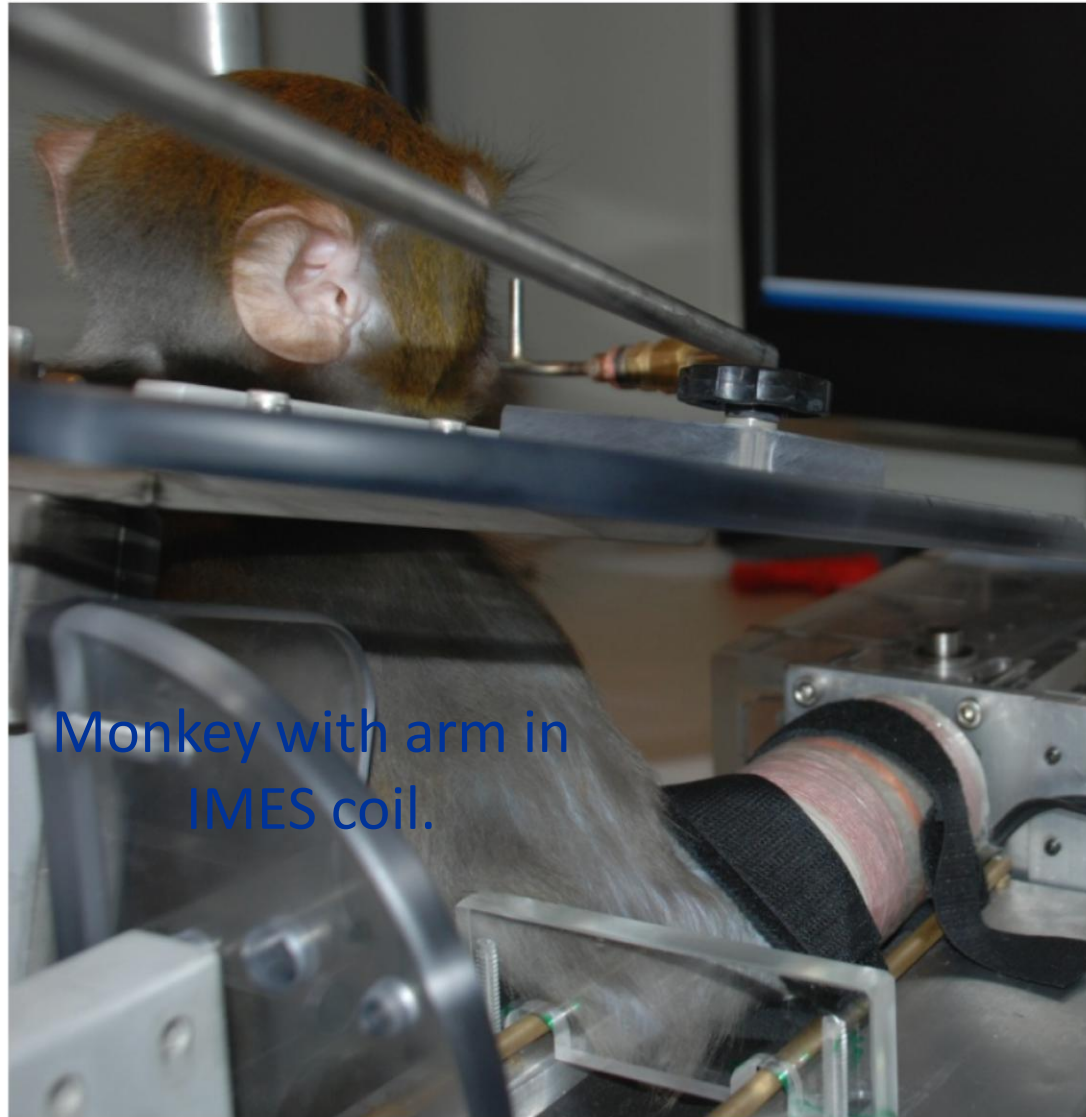


RELAXED

FLEX

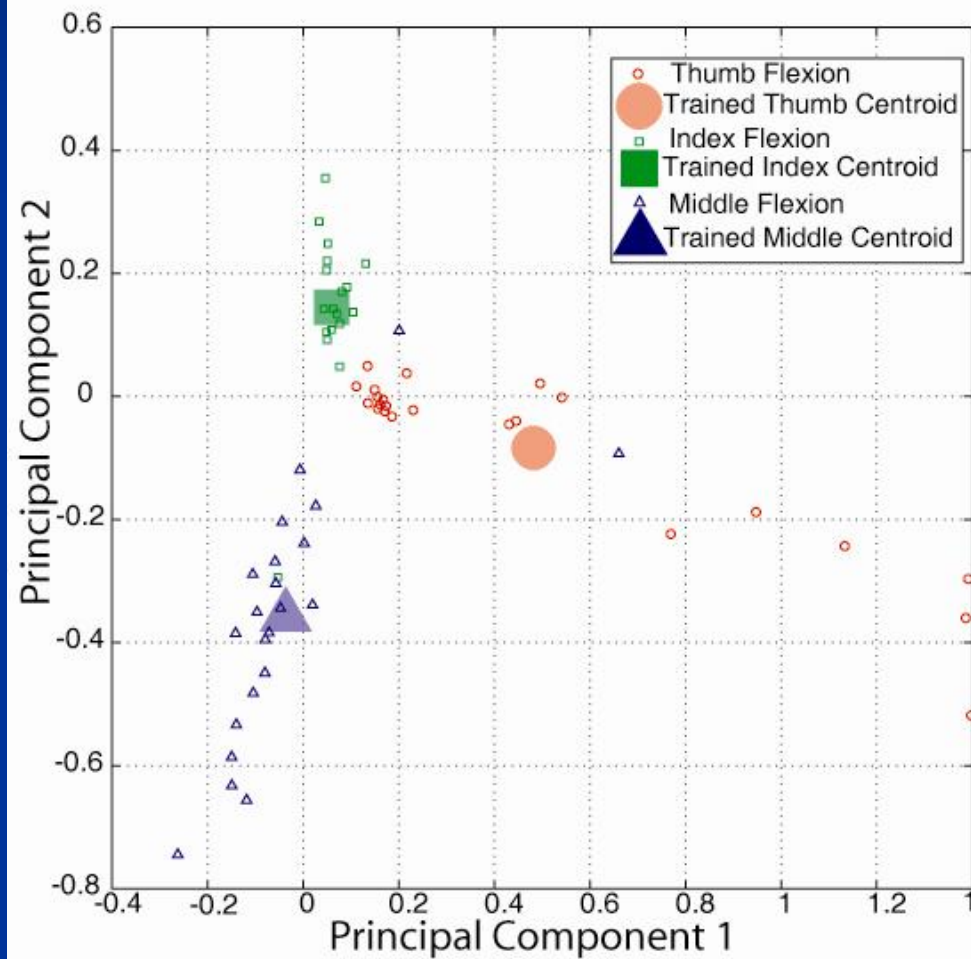
CUE

EMG RAW DATA

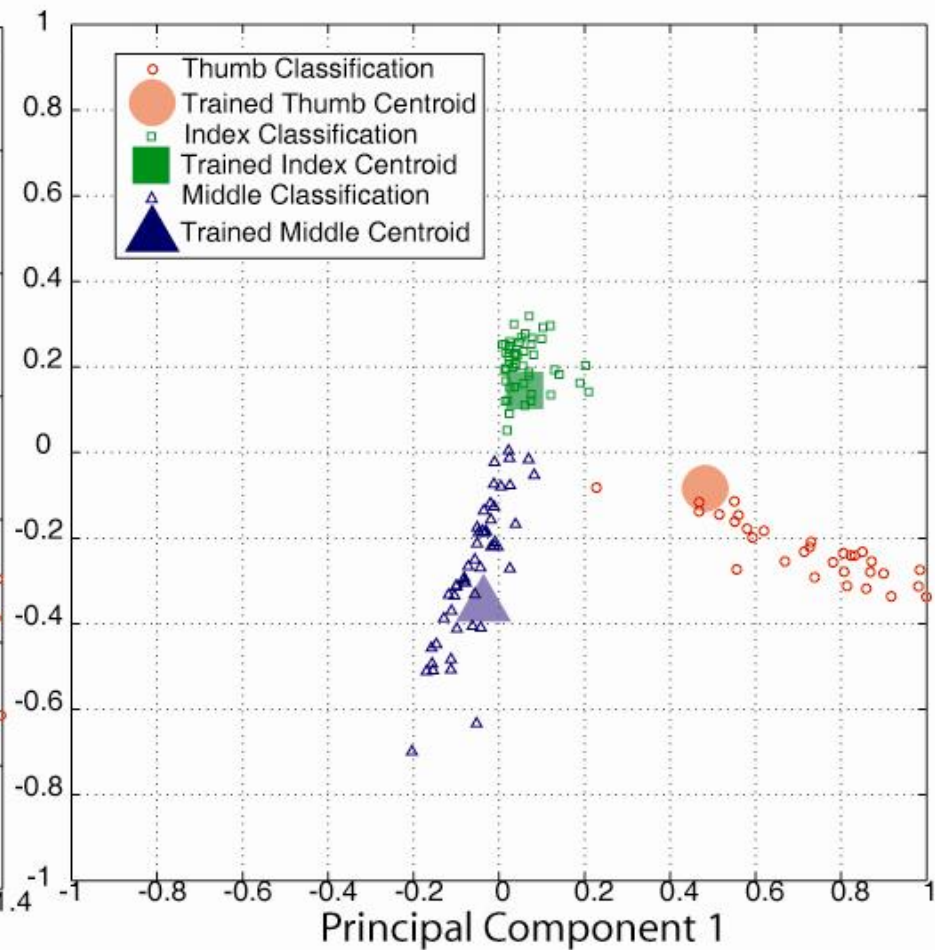


DECODE TRAINING & TESTING PLOTS

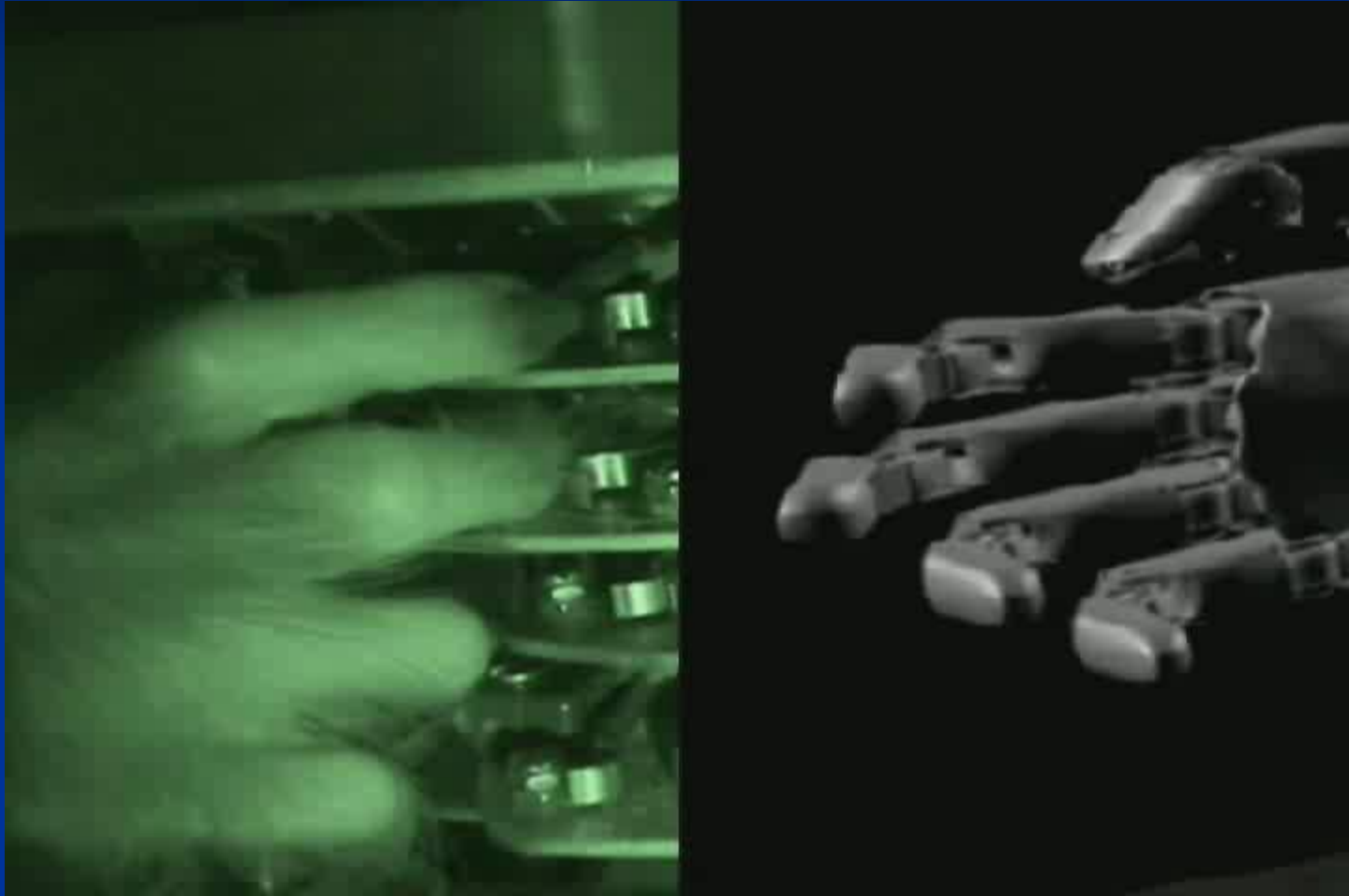
TRAINING



TESTING: predictability 95%

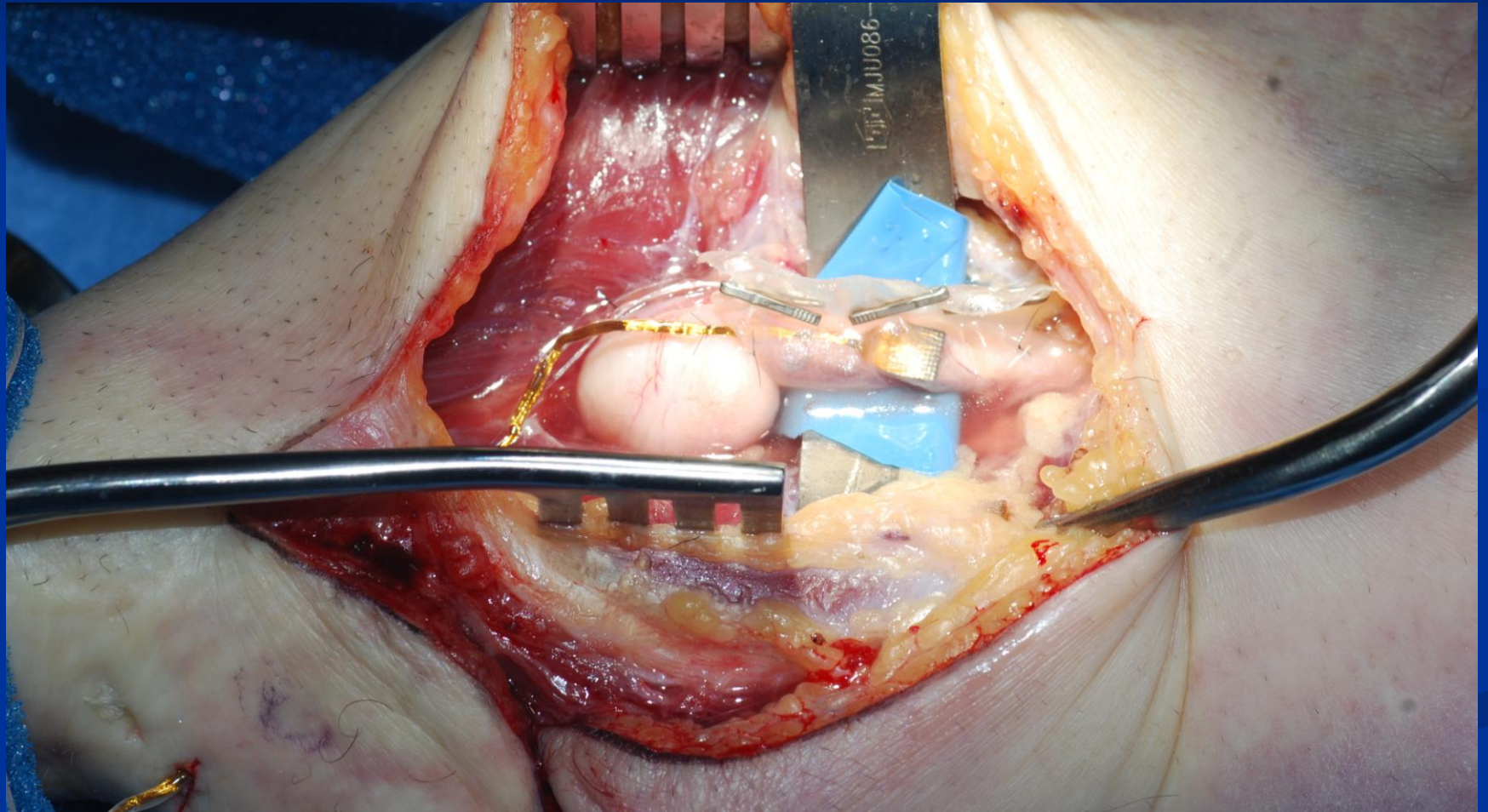


CONTROLLING VIRTUAL HAND



SUMMARY

- Very small individuated finger flexions can be correctly decoded using Wireless IMES EMG signals with high accuracy
- IMES remain safe and effective for 14 months post-implantation
- IMES can offer intuitive dexterous control of artificial limbs and hands after amputation



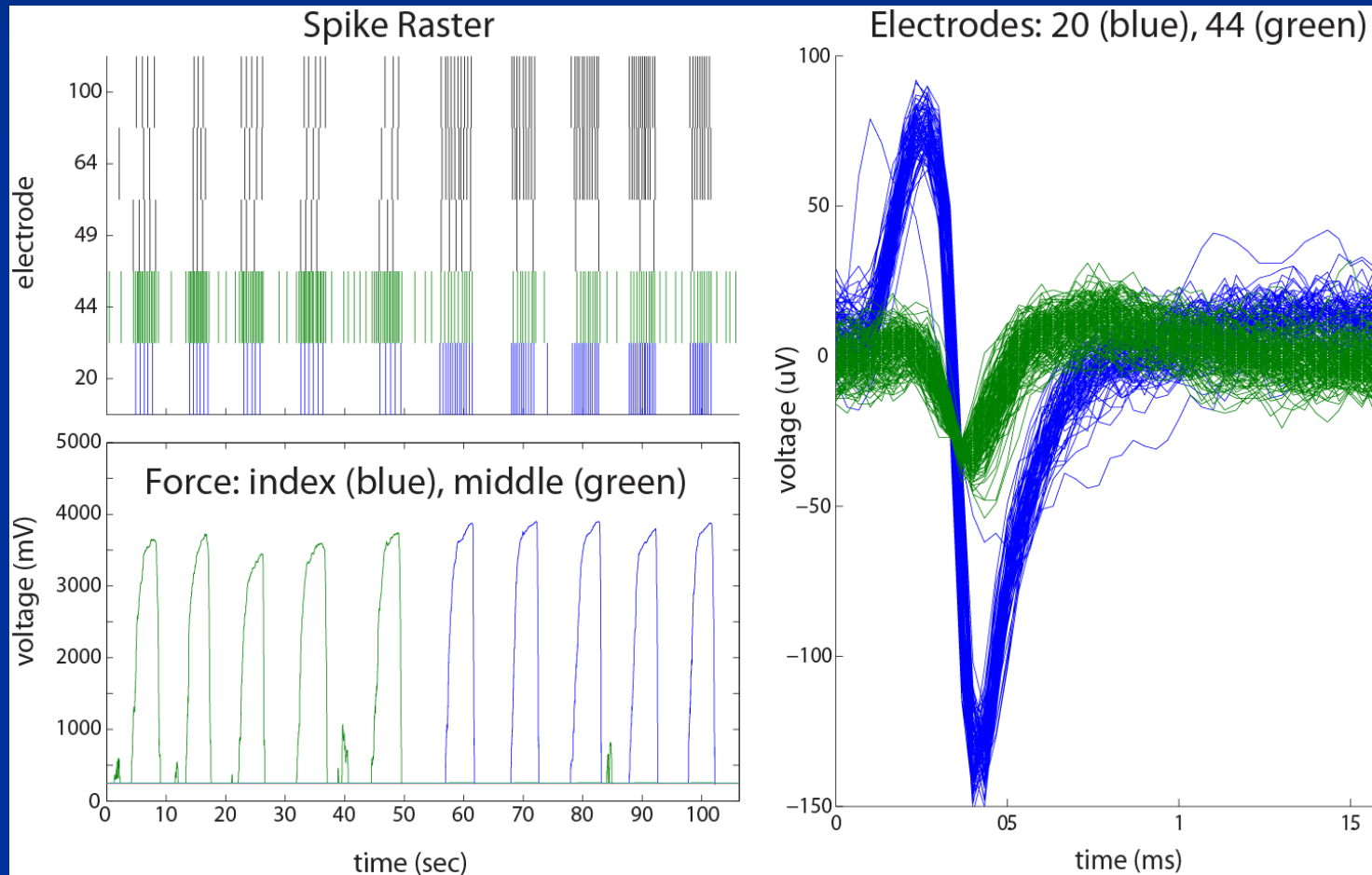
Chronic Human USEA Implant



Median N. = 11.5 mm width

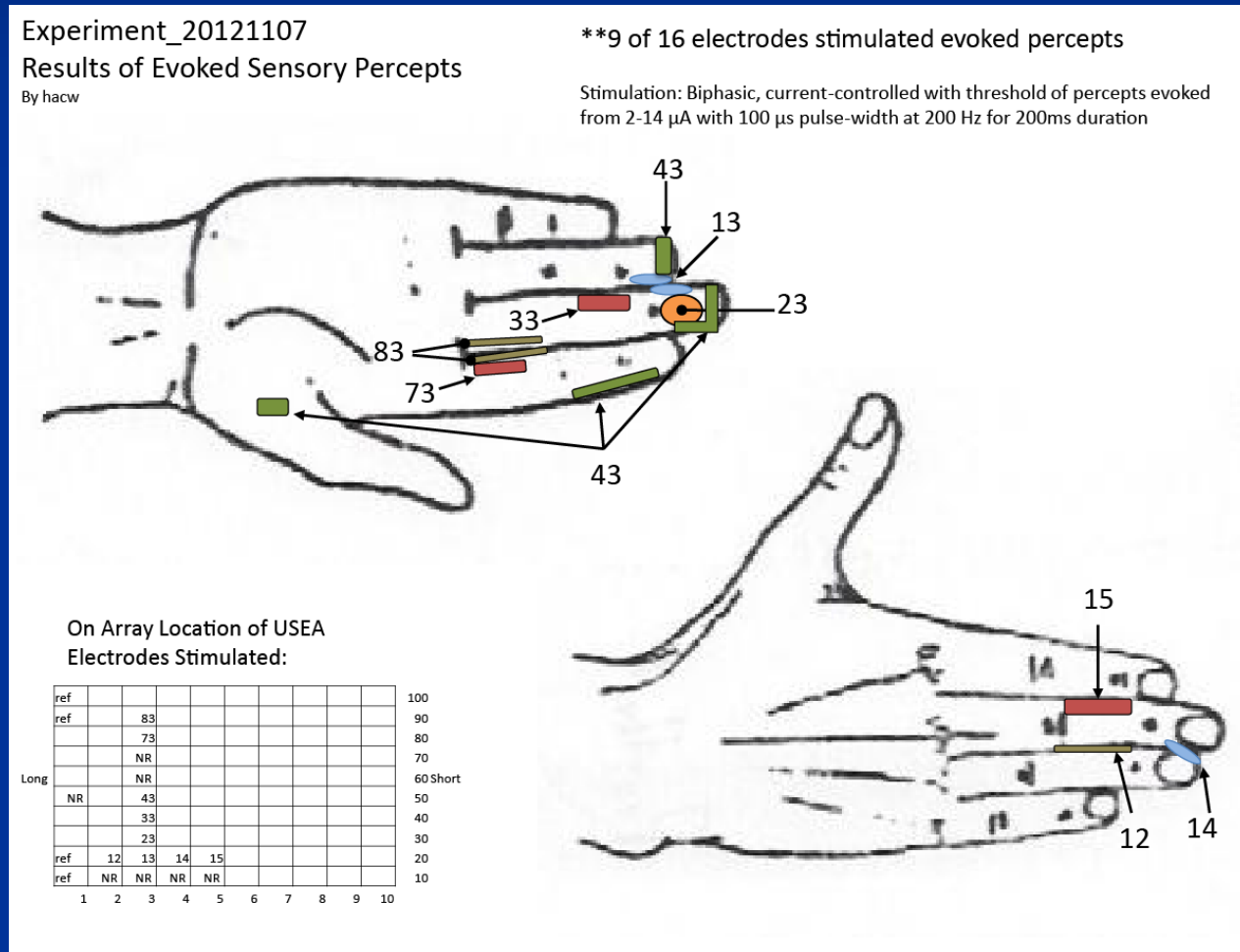
3. TA4 Systems Test: Human peripheral nerve

- Isolated action potential firing correlated with index and middle finger movements

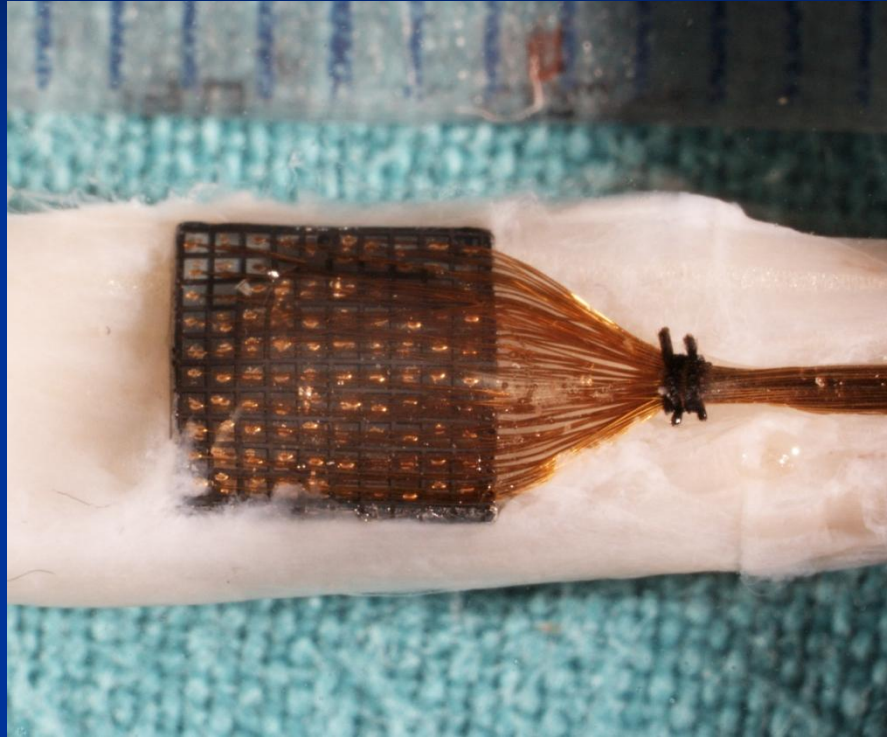


3. TA5 Sensory Feedback: Human peripheral nerve

- Somatotopic map of all evoked sensations using micro-stimulation via USEA



Human USEA Implant--Coverage



Median Nerve

My Father, circa 1965

“If it hurts we can cut it off and get a new one at the hardware store”